SPECTRUM ANALYSIS OF TROPICAL WAVES IN THE INDIAN OCEAN

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NAVAL POSTGRADUATE SCHOOL
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THESIS

SPECTRUM ANALYSIS OF TROPICAL WAVES
IN THE INDIAN OCEAN

by

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June 1974

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SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* Spectrum Analysis of Tropical Waves in the Indian Ocean		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis June 1974 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR*(s)* Jonathan Thomas Malay		8. CONTRACT OR GRANT NUMBER*(s)*
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE June 1974 13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)* Naval Postgraduate School Monterey, California 93940		15. SECURITY CLASS. *(of this report)* Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

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Three spectral peaks in the 10-17 day, 6-7 day and 4-5 day ranges have been detected. However, only the 10-17 day fluctuations seem to be prominent and appear consistently at all stations in both seasons. Cross-spectrum analysis reveals a basically in-phase structure in the vertical in the lower troposphere and reversed phase at upper levels. Evidences also indicate a northwest-southeast tilt in the Northern Hemisphere and a northeast-southwest tilt in the Southern Hemisphere. Inter-station cross-spectra and theoretical considerations suggest an estimated horizontal wavelength of approximately 3,000 km with a westward propagation direction.

Due to the limited number of available stations and the quality of data, these results are considered tentative and further study in this area is suggested.

Spectrum Analysis of Tropical Waves

in the Indian Ocean

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

NAVAL POSTGRADUATE SCHOOL
June 1974

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An attempt has been made to identify tropical waves with periods less than 20 days in the Indian Ocean by spectrum analysis of radiosonde data for five stations, widely scattered over the Indian Ocean area. The data used is for the period from January to September, 1973, which was further divided into two five-month seasons, overlapping in May due to consideration of the monsoonal shift in the mean flow.

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ACKNOWLEDGEMENT

The author wishes to express his thanks to Dr. G. J. Haltiner for his encouragement to undertake this project and to Dr. C.-P. Chang for his invaluable guidance, without which this project could never have been completed.

I. INTRODUCTION

In the past 30 years, numerous attempts have been made to identify and develop models of large-scale wave disturbances in the tropics. Riehl (1945, 1954) was among the first to study these disturbances. He observed what he termed "Waves in the Easterlies" or "easterly waves" through synoptic map analysis. The identification of the easterly waves and documentation of their associated weather patterns and changes were the focal points of these early studies.

The early synoptic approach has had serious limitations due to the lack of density of reporting stations at low latitudes, and further because of the lack of an adequate theoretical framework. Also, the validities of these case studies are quite limited because of the sample size.

The use of spectrum analysis has been found to be an effective alternate approach by a number of researchers in the last six years. By use of high speed computers, a great deal of quantitative statistics can be compiled on the character of tropical waves. Through the inspection of the power spectrum distribution, it is possible to identify and isolate major fluctuation periods in the data. Then, by application of cross-spectrum analysis, the correlation of pairs of time series as a function of frequency, one may deduce the structure of these fluctuations and evaluate their significance.

To date, the most extensive research using spectrum analysis has been done in the tropical Pacific Ocean because of the existence of a relatively good observational network. The two groups which have contributed significantly in this area are Yanai and his collaborators at the University of Tokyo who used data from Central Pacific stations; and Wallace and his collaborators at the University of Washington who used Western Pacific stations. Both groups consistently found a wave period of 4-5 days, suggesting that they might be identified as easterly waves. Yanai et al (1968) and Nitta (1970) estimated the horizontal wavelength of these waves to be 6,000 - 10,000 km while Wallace and Chang (1970), Chang et al (1970) and Wallace (1971) set their estimate of the wavelength on the order of 4,000 km.

In addition to the 4-5 day period, Wallace and Chang (1969) found 10-15 day fluctuations with a horizontal wavelength of the order of 10,000 km in the zonal wind component. Later, Yanai and Murakami (1970) also found fluctuations in this component with periods of ten days and longer at most of the Central Western Pacific stations that they studied.

Studies in other areas have also been carried out. Krishnamurti and Kanamitsu (1972) identified cold-core waves in the lower troposphere over the Caribbean Sea with a westward propagation of six degrees per day. Burpee (1972, 1974) has done extensive work using spectrum analysis for stations in northwestern Africa during the Northern Hemisphere summer. Again, he found a dominant fluctuation of 4-5 days with a

horizontal wavelength of 1,900 - 4,100 km. These waves propagate westward with a maximum amplitude at 20° at 25° north.

So far, the studies in the Indian Ocean appear to be inadequate. Parker (1973), in a spectral study of 100 mb winds over Gan attempted to identify the equatorial Kelvin waves of wavenumber one in the lower stratosphere and upper troposphere. He did find downward propagating waves similar to the Kelvin waves; however, they have a periodicity greater than a month which is somewhat longer than the Kelvin waves observed by Wallace and Kousky (1968). Rao and Murty (1972) attempted to identify the equatorial waves, which were described by Yanai and Murakami in the tropical Pacific, over the area east of the Indian Ocean. They found some evidence to believe that such waves do indeed exist in their region of study. The stations included in their analysis were Singapore, Byan Lepas and Saigon. Results of spectrum analysis in this study show some indication of a 4-5 day period wave, but lack of vertical correlation of power spectral peaks for the same parameter at each station tends to indicate some uncertainty as to the significance of the 4-5 day fluctuations.

In view of the lack of understanding for tropical waves in the Indian Ocean, the purpose of this study is to use the limited observational network available in this area to carry out a spectral study, in the hope that some new information would be found and which may be helpful for further studies.

II. DATA AND ANALYSIS PROCEDURE

Radiosonde data for the eight Indian Ocean stations listed in Table I were first obtained from the National Weather Records Center at Asheville, North Carolina. One year's data, beginning in October of 1972, had been requested to coincide with the expected assumption of sounding duty by the United States Navy at Diego Garcia in that month. This small British-owned island is centrally located in the Indian Ocean. Its position and those of the surrounding stations for which data was requested are suitably oriented for inter-station analysis. As seen in Figure 1, there is good north-south and east-west pairing of stations.

However, upon inspection of the raw data prior to analysis, it was quite noticeable that Diego Garcia, Diego Suarez and Djakarta had reported so infrequently that these three stations had to be eliminated from the study. The decision was then made to continue to examine the other five stations because of the reasonable relative positioning of Gan, Minicoy, Singapore and Cocos Island. Dar-es-Salaam was also included for single station analysis. The use of only these stations meant that, due to the large separation between them, the horizontal structure of the waves deduced must be considered tentative.

Time series were generated from all remaining stations for twice daily reports of geopotential, zonal (u) and

meridional (v) wind components and temperature at the 850, 700, 500 and 300 mb levels. In addition, wind and temperature were also used at 200 mb and 100 mb and temperature only was used below 850 mb. Other data was excluded because of the many gaps contained in them.

Wind data at Cocos Island and Singapore was, on the average, about 70% complete at the levels used while all other data averaged nearly 50% completeness. Each time series was made complete by straight linear interpolation in time for missing units of the series.

The spectrum and cross-spectrum analysis was performed on the IBM 360 computer at the W. R. Church Computer Center of the Naval Postgraduate School. The program used was BMD02T of the UCLA Biomedical Statistical Program Package. Fifty lags were used which corresponds to a lag period of 25 days. For this number of lags, the program gives spectral information at frequency intervals of .02 cycles per day.

In order to examine and compare the summer and winter monsoon periods, each time series was divided into two separate periods. In the Northern Hemisphere winter, the Indian Ocean is in the regime of the easterly trade winds found all year in other tropical oceanic areas. With the advent of the summer monsoon, however, the southeast trades of the Southern Hemisphere, on crossing the equator, are turned by the coriolis acceleration and approach the Indian Peninsula, Malasia and Southeast Asia from a southwesterly

direction. The seasonal shifts between these two periods, caused by the differential heating of land and sea, occur sometime in the periods of October to November and April to May. Figure 2 gives an example of the spring shift in the zonal wind at Minicoy.

Since it was considered desirable to minimize the effect of the shifting periods and yet maximize data use and series lengths, the period of October to December, 1972 was eliminated from the study. The remaining nine-month period of January to September, 1973 was then separated into two periods of five months each, overlapping in the entire month of May. For this study, the two periods can be considered representative of the winter season and the summer season, respectively.

Before analysis was performed, each time series was twice filtered. First, a two-point running mean was used to eliminate diurnal fluctuations (frequency = 1 cycle per day). Most studies of this nature have not taken this step because the power associated with high-frequency fluctuations (greater than 0.5 cycles per day) is small, and meaningless as well for stations not reporting twice daily. However, because of the linear interpolation using 0000GMT and 1200GMT observations interchangeably, this low-pass filter was used only to maintain consistency.

A test run of BMD02T using data modified only with the low-pass filter revealed that all possible spectral peaks were obscured by low-frequency oscillations (red noise)

associated with the monsoon circulation, and that it was necessary to again filter the data, this time using a high-pass filter. An 89-point Gaussian filter designed by Holloway (1958) was used. Weights were calculated by the expression

$$w(t) = (2\pi\sigma)^{-1/2} \exp(-t/2\sigma^2)$$

using a standard deviation, $\sigma = 8$. The procedure used for filtering is as follows. If P(I) is the value at a particular time in a time series and $\bar{P}(I)$ is the sum of the weighted values, then the new (filtered) series is made up of the differences, $\bar{P}(I) - P(I)$. The frequency response to this filter is given by

$$R(f)_{\bar{p}} = \exp\ (-2\pi^2\sigma^2 f^2)$$

and

$$R(f)_{\bar{p}-p} = 1-R(f)_{\bar{p}}$$

which is shown in Figure 3. Notice that for periods less than or equal to 20 days, the response is greater than or equal to 95%.

The filters were applied to the entire nine-month period from January to September which consisted of 272 days or 544 data points. Filtering caused 22 days to be lost from either end of a time series. The series was then divided as described earlier into two time series of 123 days or 246 data points.

III. RESULTS

A. POWER SPECTRA

Due to the high-pass filter, spectral estimates for frequencies .00 to .04 are greatly reduced. Therefore, any spectral peak at .06 cycles per day, regardless of how distinct it may be, can only be viewed as an indication of large power in the low-frequencies. However, any clear spectral peak at frequencies .08 cycles per day or greater may be considered meaningful.

Since 250 power spectrum distributions were generated in this study (25 for each of five stations for two seasons) and it would require a substantial amount of space to show all of them, a code was devised for summarizing the observed spectral peaks. Figure 4 shows the power spectrum distributions for a number of the time series at Gan in the winter season. Near each spectral peak, a digit is placed which is descriptive of the character of that peak and how it relates to the power distributions at other frequencies. A "0" indicates that the dominant peak is at the low-frequency limit of the filter and is indicative only of fluctuations of periods greater than 17 days. A "1" indicates the largest spectral peak, aside from possibly a low frequency peak. A "2" represents a peak also to be considered significant but with less associated power than the former two. A "3" indicates a relatively small-power, one point peak in the curve

which may not be very significant unless it is also supported by similar or stronger peaks at other levels or in other related parameters. The spectra for all series are summarized this way in Tables II - XI. By study of these power spectrum distributions, a number of observations can be made. First, spectral peaks in three frequency ranges appear to be predominant: fluctuations of frequency .06 to .10, .14 to .16 and .20 to .22 cycles per day. These frequency bands can be converted to periods of 10-17 days, 6-7 days, and 4-5 days, respectively. Of these three, the 10-17 day fluctuations appear to be most significant at each station in both the summer and winter seasons. This periodicity can also be visualized by examination of many of the time series shown in Figures 5-18. It was observed by Krishnamurti et al (1973) that the Tibetan High has a periodicity of 15 days.

Power spectral estimates, averaged across each of the three major frequency bands are listed in Tables XII - XVII. From these tables, one can determine the level of maximum strength of the fluctuations in each time series. Units are $m^2 sec^{-2}$ per $2\pi/50$ day^{-1} for velocities, $°C^2$ per $2\pi/50$ day^{-1} for temperatures and m^2 per $2\pi/50$ day^{-1} for geopotential height.

For the 10-17 day waves shown in Tables XII and XIII, it can be seen that for most cases, fluctuations in wind components and in geopotential height increase with height while temperature fluctuations have minima at 500 mb and maxima above and below. On the average, the fluctuations in u and

v are of the same order of magnitude and vary from approximately 5 m sec^{-1} at low levels to 20 m sec^{-1} or more at upper levels. Power is generally greater in u than in v, however. Also, in both seasons, there are relative minima in the fluctuations in zonal wind at Dar-es-Salaam and Cocos Island. Temperature fluctuations are about 2-3°C at 500 mb and 5-6°C at upper and lower levels. Geopotential height fluctuations vary from 15-25 m at 850 mb to approximately 400 m in some upper-level series.

Tables II-XI and XIV-XVII indicate that 6-7 and 4-5 day fluctuations have generally less significance, especially in the summer seasons. Two exceptions to this are Cocos Island, where the 6-7 day fluctuations appear to be prominent throughout the troposphere, and at Gan where this same periodicity is prominent in low-level time series (see Figure 19). It is possible that these shorter period fluctuations may be the result of disturbances with spatial scales somewhat less than the distances between stations. This is suggested by the dissimilarity of features of the spectral estimates in these frequency bands among the different stations.

B. CROSS-SPECTRUM OF 10-17 DAY WAVES

Cross-spectrum analysis between levels, parameters and stations have been carried out with the results on the 10-17 day period range given in Tables XIX-XXIII. These cross-spectra were averaged for the .06, .08 and .10 cycles per day frequencies. In answer to the question of statistical significance, the degrees of freedom were estimated to be 15

taking into account the smoothing of the spectra and the averaging of values over a spectral band. It was roughly determined that for the 10-17 day fluctuations, coherence square values greater than .15 and .19 are significant to the 90 and 95% levels, respectively. These levels were calculated using the probability points of distributions of squared coherence compiled by Amos and Koopmans (1963). Values with significance at less than the 90% level were omitted from the tables and phase differences corresponding to levels 90 to 95% are shown in parentheses.

Tables XX and XXI show results from inter-level cross-spectrum analysis between 850 mb and other levels for 10-17 day fluctuations. In the winter season, there is a phase shift of a half cycle at Gan and Minicoy and a quarter to a third cycle at Singapore and Dar-es-Salaam between meridional wind series at lower (below 500 mb) and upper (above 300 mb) levels. This may be considered an indication of a warm-core structure. The minima in spectral estimates of zonal wind at 500 mb at Minicoy, Dar-es-Salaam and Cocos Island observed in Tables XII and XIII support the assumption of a middle-level node implied by the warm-core structure. For those stations not having a minima at 500 mb, it may be because the node is situated between the vertical-resolution of the levels used.

Inter-parameter cross-spectrum analysis was performed for the 10-17 day fluctuations in winds at 850, 700 and 300 mb and the results are listed in Table XX. At 850 mb,

u is observed to be leading v at each station with phase differences up to .44 cycle as seen at Cocos Island. The larger phase differences at this level occur at Minicoy and Cocos Island which are the two stations most distant from the equator. This is an indication of a horizontal tilt in the waves with the direction of the tilt depending on the direction of propagation of the waves. Results of cross-spectrum analysis of wind and temperature series yields little information due to low significance.

Zonal and meridional wind components were crossed for pairs of stations with results significant to the 90% level listed in Table XXI. Unfortunately, many cross-spectra are below the significant level. However, from the few remaining values and from results previously discussed, a tentative zonal structure for the 10-17 day waves can be deduced. As seen in Figure 1, pairs of Gan-Singapore and Minicoy-Singapore are east-west oriented with only a few degrees difference in latitudes. The distances between Gan and Singapore and between Minicoy and Singapore are approximately 3,400 and 3,700 km, respectively. The 850 mb u component at Gan lags that at Singapore by either 10% or 110% of a cycle which can indicate four possible wavelengths. If the waves are propagating westward, the horizontal wavelengths could be either 34,000 or 3,000 km. If they propagate eastward, the wavelengths could be either 3,800 or 1,900 km. Using the information that the 700 mb series at Minicoy lags that at Singapore by a fifth of a cycle (or six fifths of a

cycle), the possible wavelengths are 9,000 or 2,600 km for westward propagation and 6,000 or 2,250 km for eastward propagation.

It is unlikely that the longer wavelengths mentioned are really possible because they are not nearly the same between the two pairs of stations and because the low coherence square values observed would not be expected for such long waves. There are only two reasonable possibilities, then, and they are that the wavelengths are of the order of 3,000 km for westward propagating waves and of the order of 2,000 km for eastward propagating waves. Now, equatorial wave theories [Matsuno (1966) and Lindzen (1967] predict that all waves move westward relative to the mean zonal flow except Kelvin waves which are prominent in the u component only. If one eliminates the possibility that these are Kelvin waves because of the observed power in the v spectra, then the only remaining possible wavelength at low levels for these 10-17 day waves is about 3,000 km for a westward propagation.

Cross-spectrum analysis for the other two period ranges (6-7 and 4-5 days) were also carried out but the results generally fall below the 90% significance level.

IV. SUMMARY AND CONCLUDING REMARKS

Power spectrum analysis has revealed spectral peaks in the 10-17 day, 6-7 day and 4-5 day ranges. Of these three, only the 10-17 day fluctuations seem to be prominent and appear consistently at all stations in both seasons. Cross-spectrum analysis has been used to formulate a possible structure of the 10-17 day waves. There is a basically in-phase structure in the vertical with reversed phase at upper levels. Evidences also indicate a northwest-southeast tilt in the Northern Hemisphere and a northeast-southwest tilt in the Southern Hemisphere. Inter-station cross-spectra and theoretical considerations suggest an estimated horizontal wavelength of approximately 3,000 km with a westward propagating direction.

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TABLE I

LIST OF STATIONS

Station	Latitude	Longitude	WMO No.	Elevation (ft)
Gan	S 00-41	E 73-09	41350	6
Minicoy	N 08-18	E 73-00	43369	6
Singapore	N 01-21	E 103-54	48694	33
Diego Garcia*	S 07-14	E 72-26	61697	7
Dar-es-Salaam	S 06-53	E 39-12	63894	190
Diego Suarez*	S 12-21	E 49-18	67009	346
Djakarta/* Kemajoram	S 06-09	E 106-11	96743	16
Cocos Island	S 12-11	E 96-50	96996	16

*Data not analyzed due to incompleteness.

		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28
GEOPOTENTIAL	1000 mb.	0								2			
	850 mb.		1							3			
	700 mb.	0											
	500 mb.	0											
	300 mb.	0											
U COMPONENT	850 mb.	0			2 —	2 —	2						3
	700 mb.	0						3			3		
	500 mb.	0						3					
	300 mb.	0											
	200 mb.	0											
	100 mb.	0											
V COMPONENT	850 mb.			2		1							
	700 mb.			1			3						
	500 mb.			1									
	300 mb.	0											
	200 mb.	0								3			
	100 mb.		1					2					
TEMPERATURE	Surface		1 —	1									
	1000 mb.		1										
	850 mb.		1							3			
	700 mb.		1						3				
	500 mb.	0			1 —	1							
	300 mb.		1		3								
	200 mb.	0		1									
	100 mb.	0											
		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28

TABLE II. Spectral peaks at Gan, winter season, for selected frequencies (cycles per day).

		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28
GEOPOTENTIAL	1000 mb.	0											
	850 mb.		1							1			
	700 mb.	0								2			
	500 mb.	0				1			3				
	300 mb.		1			3							
U COMPONENT	850 mb.		1			3					2		
	700 mb.		1						3				
	500 mb.	0							2				
	300 mb.	0	1			3				3			
	200 mb.		1										
	100 mb.		1			3							
V COMPONENT	850 mb.	0	1						3				
	700 mb.	0							3				
	500 mb.	0						2	2				
	300 mb.	0		1									
	200 mb.	0											
	100 mb.		1										
TEMPERATURE	Surface		1				2						
	1000 mb.		1		3 —	— 3							
	850 mb.	0					3						
	700 mb.	0		1				3					
	500 mb.	0			3								
	300 mb.	0	1		3 —	— 3			3				
	200 mb.	0	1				2						
	100 mb.												
		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28

TABLE III. Spectral peaks at Minicoy, winter season.

		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28
GEOPOTENTIAL	1000 mb.	0											
	850 mb.	0											
	700 mb.	0		1						3			
	500 mb.	0						3					
	300 mb.	0				1							
U COMPONENT	850 mb.		1										
	700 mb.	0				2							
	500 mb.	0											
	300 mb.	0					3						
	200 mb.	0			3								
	100 mb.	0			2 —	— 2							
V COMPONENT	850 mb.			1									
	700 mb.		1 —	— 1				2					3
	500 mb.		1			1 —	— 1			2			3
	300 mb.					1					3		
	200 mb.		1					2 —	— 2				
	100 mb.	0											
TEMPERATURE	Surface			1			3				2		
	1000 mb.		1 —	— 1								3	
	850 mb.		1		1					2			
	700 mb.	0			2					3			
	500 mb.	0			1 —	— 1				3			
	300 mb.	0	1		2 —	— 2			3				
	200 mb.	0		1 —	— 1 —	— 1 —	— 1						
	100 mb.	0											
		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28

TABLE IV. Spectral peaks at Singapore, winter season.

		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28
GEOPOTENTIAL	1000 mb.	0		3									
	850 mb.			1					3				
	700 mb.	0		1									
	500 mb.	0				1 —	— 1						
	300 mb.		1			3					2		
U COMPONENT	850 mb.	0				3							
	700 mb.	0											
	500 mb.	0				2				3			
	300 mb.		1										
	200 mb.	0			2								
	100 mb.			1									
V COMPONENT	850 mb.	0										3	
	700 mb.		1		1 —	— 1					3		
	500 mb.		1							3			
	300 mb.			1				3					
	200 mb.	0								3			
	100 mb.	0											
TEMPERATURE	Surface	0	1			1							
	1000 mb.	0				1							
	850 mb.	0			3								
	700 mb.	0					1 —	— 1					
	500 mb.	0				1 —	— 1						
	300 mb.	0					1 —	— 1					
	200 mb.	0							2				
	100 mb.	0		3					2				
		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28

TABLE V. Spectral peaks at Dar-es-Salaam, winter season.

		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28
GEOPOTENTIAL	1000 mb.	0											
	850 mb.	0			1			3					
	700 mb.	0						3					
	500 mb.		2				3						
	300 mb.		1				1				2		
U COMPONENT	850 mb.	0				1							
	700 mb.		2			1							
	500 mb.	0		1		2							
	300 mb.		1 —	— 1		3							
	200 mb.					1							
	100 mb.	0	3 —	— 3									
V COMPONENT	850 mb.		2			1					2		
	700 mb.	0							2				
	500 mb.		1			3			2				
	300 mb.		1 —	— 1					2 —	— 2			
	200 mb.		1										
	100 mb.	0		1 —	— 1								
TEMPERATURE	Surface	0						1 —	— 1				
	1000 mb.	0			3			3					
	850 mb.	0				1							
	700 mb.	0						3			3		
	500 mb.	0		3			2						
	300 mb.	0		3									
	200 mb.		1			3 —	— 3		3				
	100 mb.	0		1 —	— 1			3					
		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28

TABLE VI. Spectral peaks at Cocos Island, winter season.

		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28
GEOPOTENTIAL	1000 mb.	0							3				
	850 mb.	0											
	700 mb.	0		2					3				
	500 mb.	0											
	300 mb.	0											
U COMPONENT	850 mb.	0											
	700 mb.	0											
	500 mb.		1										
	300 mb.	0											
	200 mb.	0		2									
	100 mb.	0											
V COMPONENT	850 mb.	0											
	700 mb.	0											
	500 mb.	0			1								
	300 mb.			1									
	200 mb.	0			2								
	100 mb.	0		1									
TEMPERATURE	Surface		1 —	1							2		
	1000 mb.	0		1			2						
	850 mb.	0											
	700 mb.	0						2					
	500 mb.		1										
	300 mb.	0											
	200 mb.			1									
	100 mb.	0											
		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28

TABLE VII. Spectral peaks at Gan, summer season.

		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28
GEOPOTENTIAL	1000 mb.	0			2 —	— 2							
	850 mb.	0											
	700 mb.	0		2 —	— 2								
	500 mb.		1										
	300 mb.		1				3						
U COMPONENT	850 mb.	0											
	700 mb.	0											
	500 mb.	0		2				2					
	300 mb.	0	1				2					3	
	200 mb.			1			2						
	100 mb.	0											
V COMPONENT	850 mb.		1										
	700 mb.		1										
	500 mb.	0	1				2 —	— 2					
	300 mb.	0		1								3	
	200 mb.	0								3			
	100 mb.		1			2							
TEMPERATURE	Surface	0				1							
	1000 mb.	0				1							
	850 mb.	0											
	700 mb.	0	1			1							
	500 mb.		1										
	300 mb.		1				2						
	200 mb.			1									
	100 mb.												
		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28

TABLE VIII. Spectral peaks at Minicoy, summer season.

		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28
GEOPOTENTIAL	1000 mb.	0											
	850 mb.	0		1									
	700 mb.			1									
	500 mb.			1									
	300 mb.	0		2			3						
U COMPONENT	850 mb.	0				1							
	700 mb.	0											
	500 mb.	0	1										
	300 mb.	0											
	200 mb.	0	2			3							
	100 mb.		1										
V COMPONENT	850 mb.			1									
	700 mb.		1							3			
	500 mb.		1										
	300 mb.	0											
	200 mb.	0		2					3				
	100 mb.	0				3							
TEMPERATURE	Surface	0		1						2			
	1000 mb.	0		1						2			
	850 mb.	0		1						3 —	— 3		
	700 mb.	0		1									
	500 mb.		1				1						
	300 mb.	0											
	200 mb.	0	2		1 —	— 1							
	100 mb.	0											
		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28

TABLE IX. Spectral peaks at Singapore, summer season.

		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28
GEOPOTENTIAL	1000 mb.	0			3			3					
	850 mb.	0			2								
	700 mb.		1	1									
	500 mb.	0	1				3						
	300 mb.	0				1							
U COMPONENT	850 mb.	0	3			3							
	700 mb.	0	1			3							
	500 mb.	0			1			1	1				
	300 mb.	0											
	200 mb.	0											
	100 mb.	0											
V COMPONENT	850 mb.	0								1			
	700 mb.				1					2			
	500 mb.	0		1				3					
	300 mb.		1										
	200 mb.		1							2			
	100 mb.	0											
TEMPERATURE	Surface	0		1	1					1			
	1000 mb.					1				3			
	850 mb.	0		1									
	700 mb.	0					2						
	500 mb.	0					3						
	300 mb.				1								
	200 mb.	0			1								
	100 mb.	0					2						
		.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28

TABLE X. Spectral peaks at Dar-es-Salaam, summer season.

TABLE XII.

POWER SPECTRAL ESTIMATES FOR 10-17 DAY WAVES IN THE WINTER SEASON. VALUES ARE AVERAGED FOR FREQUENCIES .06, .08 AND .10 CYCLES PER DAY.

Station	Level	u	v	T	Geopotential
Gan	850mb	6.7	4.8	3.4	74.5
	700	16.8	4.5	0.6	96.7
	500	23.2	9.3	1.1	5706.6
	300	45.7	8.3	6.5	877.9
	200	79.6	27.4	3.3	
Minicoy	850	5.9	7.9	1.0	136.0
	700	10.2	4.4	1.7	215.9
	500	17.9	8.3	1.5	199.7
	300	12.6	9.6	2.4	3837.5
	200	35.1	25.7	1.1	
Singapore	850	7.3	5.7	1.3	30.3
	700	10.1	8.5	0.5	126.4
	500	15.6	2.0	0.4	1247.0
	300	30.7	4.2	3.5	2140.0
	200	24.4	9.2	0.3	
Dar-es-Salaam	850	4.6	6.2	2.5	338.4
	700	15.2	3.6	0.9	1963.5
	500	9.3	7.8	0.4	446.5
	300	24.5	9.2	2.0	848.1
	200	26.6	23.0	1.0	
Cocos Island	850	10.8	4.1	0.4	38.3
	700	15.7	8.3	0.6	73.8
	500	12.5	12.0	0.7	1371.6
	300	17.1	12.9	3.8	24082.4
	200	17.2	33.0	0.4	

TABLE XIII

POWER SPECTRAL ESTIMATES FOR THE 10-17 DAY WAVES IN THE SUMMER SEASON. VALUES WERE AVERAGED FOR FREQUENCIES .06, .08, AND .10 CYCLES PER DAY.

Station	Level	u	v	T	Geopotential
Gan	850	16.2	7.1	0.5	38.8
	700	14.5	9.6	0.4	57.1
	500	27.4	7.4	2.0	2553.3
	300	24.6	11.2	1.2	284.0
	200	60.8	8.5	2.1	
Minicoy	850	11.9	10.8	4.5	162.4
	700	18.4	8.3	0.5	182.8
	500	12.7	3.9	2.1	532.4
	300	12.3	6.7	4.1	1857.3
	200	13.6	14.3	1.7	
Singapore	850	5.4	4.9	0.7	51.9
	700	13.5	7.6	0.7	231.4
	500	16.5	45.2	9.7	330.7
	300	25.9	171.3	4.7	459.4
	200	19.5	37.1	0.4	
Dar-es-Salaam	850	4.0	13.9	1.6	339.9
	700	18.4	2.4	2.1	2067.5
	500	9.2	14.6	0.8	1097.7
	300	44.3	31.5	0.4	625.7
	200	48.5	30.1	1.2	
Cocos Island	850	24.3	10.4	1.1	140.2
	700	24.1	14.5	1.4	113.5
	500	15.6	18.4	1.5	152.7
	300	48.0	26.0	5.3	371.3
	200	41.3	34.9	2.3	

TABLE XIV

POWER SPECTRAL ESTIMATES FOR 6-7 DAY WAVES IN THE WINTER SEASON. VALUES WERE AVERAGED FOR FREQUENCIES .14 AND .16 CYCLES PER DAY.

Station	Level	u	v	T	Geopotential
Gan	850	5.0	5.3	2.1	10.7
	700	3.8	3.1	0.1	35.0
	500	5.9	7.7	0.9	2702.7
	300	16.0	5.9	3.8	451.8
	200	11.0	11.2	1.3	
Minicoy	850	3.6	2.4	0.4	22.6
	700	4.2	2.3	0.8	94.7
	500	6.2	2.6	0.8	169.8
	300	8.8	4.8	1.3	2455.5
	200	8.6	7.3	0.8	
Singapore	850	1.7	2.1	1.0	19.6
	700	6.7	2.8	0.3	80.3
	500	2.1	2.4	0.4	665.4
	300	5.9	6.2	1.3	2408.2
	200	10.0	2.7	0.3	
Dar-es-Salaam	850	1.8	2.5	1.7	220.8
	700	1.9	3.8	0.4	1113.4
	500	7.6	3.0	0.6	860.4
	300	4.4	2.9	2.2	723.9
	200	15.9	7.5	0.4	
Cocos Island	850	11.3	7.5	0.4	27.6
	700	20.0	3.7	0.3	22.3
	500	13.4	6.9	0.5	965.5
	300	13.5	5.9	0.8	21980.6
	200	28.5	11.2	0.4	

TABLE XV

POWER SPECTRAL ESTIMATES FOR 6-7 DAY WAVES IN THE SUMMER SEASON. VALUES WERE AVERAGED FOR FREQUENCIES .14 AND .16 CYCLES PER DAY.

Station	Level	u	v	T	Geopotential
Gan	850	7.5	1.4	0.2	8.4
	700	2.7	2.5	0.2	22.6
	500	3.1	4.6	0.8	1769.3
	300	7.5	6.9	0.4	186.6
	200	9.7	4.3	1.1	
Minicoy	850	5.0	1.8	0.7	62.9
	700	9.5	2.8	0.5	118.8
	500	7.2	3.3	1.1	225.4
	300	7.6	2.9	1.5	913.2
	200	7.9	4.0	1.1	
Singapore	850	4.2	2.0	0.1	29.3
	700	3.2	4.4	0.4	80.5
	500	5.2	23.5	0.7	57.0
	300	9.2	12.3	1.7	148.8
	200	12.5	7.3	0.4	
Dar-es-Salaam	850	2.3	1.1	0.8	209.8
	700	5.4	2.5	1.8	1102.4
	500	6.6	3.7	0.5	637.6
	300	13.2	9.2	0.3	559.2
	200	11.5	7.9	1.2	
Cocos Island	850	4.1	3.1	0.4	87.5
	700	2.9	4.1	0.4	115.6
	500	12.2	3.6	0.3	65.4
	300	21.3	10.6	0.9	120.8
	200	23.3	12.3	1.0	

TABLE XVI

POWER SPECTRAL ESTIMATES FOR 4-5 DAY WAVES IN THE WINTER SEASON. VALUES WERE AVERAGED FOR FREQUENCIES .20 AND .22 CYCLES PER DAY.

Station	Level	u	v	T	Geopotential
Gan	850	4.2	1.3	1.7	4.4
	700	2.0	1.9	0.1	15.7
	500	3.8	3.3	0.5	1134.7
	300	6.8	3.6	2.4	295.6
	200	8.3	6.3	0.7	
Minicoy	850	1.2	1.9	0.3	48.8
	700	3.5	1.5	0.5	73.8
	500	8.2	4.8	0.4	73.4
	300	5.3	1.2	0.9	1036.2
	200	2.7	3.7	0.4	
Singapore	850	0.6	0.7	0.4	4.5
	700	1.7	2.3	0.2	34.3
	500	0.6	1.6	0.2	544.2
	300	3.0	1.2	0.6	880.0
	200	4.2	3.7	0.1	
Dar-es-Salaam	850	0.8	0.8	0.5	132.4
	700	1.0	2.7	0.3	672.5
	500	3.4	1.3	0.2	413.2
	300	2.6	1.4	1.9	327.6
	200	4.3	6.5	0.4	
Cocos Island	850	1.2	1.8	0.2	11.9
	700	1.2	1.7	0.2	15.5
	500	5.0	4.5	0.2	777.7
	300	3.5	6.1	0.7	11281.5
	200	3.5	2.2	0.3	

TABLE XVII

POWER SPECTRAL ESTIMATES FOR 4-5 DAY WAVES IN THE SUMMER SEASON. VALUES WERE AVERAGED FOR FREQUENCIES .20 AND .22 CYCLES PER DAY.

Station	Level	u	v	T	Geopotential
Gan	850	4.0	0.5	0.1	5.5
	700	1.4	1.3	0.2	18.9
	500	1.8	1.6	0.4	1225.3
	300	2.3	1.3	0.2	133.4
	200	5.9	3.0	0.2	
Minicoy	850	2.0	0.5	0.2	62.2
	700	3.4	0.5	0.1	45.3
	500	6.5	2.3	0.4	122.4
	300	3.7	0.7	0.7	394.6
	200	3.5	3.9	0.2	
Singapore	850	1.4	0.9	0.1	19.8
	700	1.5	2.5	0.2	48.1
	500	1.8	16.8	0.3	49.1
	300	6.6	1.5	1.0	102.2
	200	3.9	9.3	0.1	
Dar-es-Salaam	850	0.9	4.7	0.6	133.5
	700	2.4	1.7	0.6	693.5
	500	7.9	3.2	0.2	388.1
	300	6.4	5.1	0.1	318.7
	200	6.2	9.8	0.3	
Cocos Island	850	3.4	2.3	0.2	28.4
	700	3.6	2.2	0.2	46.3
	500	3.0	4.2	0.3	38.0
	300	2.8	4.4	0.9	109.6
	200	4.4	4.8	0.5	

TABLE XVIIIA

COHERENCE SQUARE BETWEEN 850 MB AND OTHER LEVELS IN HUNDREDTHS FOR 10-17 DAY FLUCTUATIONS IN THE WINTER SEASON. VALUES > .15 AND .19 ARE SIGNIFICANT AT THE 90% AND 95% LEVELS, RESPECTIVELY.

Station	Parameter	700mb	500mb	300mb	200mb
Gan	u	40	16	27	-
Gan	v	42	-	20	21
Minicoy	u	-	-	-	27
Minicoy	v	68	30	-	-
Singapore	u	45	30	-	-
Singapore	v	58	32	17	27
Dar-es-Salaam	u	47	-	-	15
Dar-es-Salaam	v	20	39	34	26
Cocos Island	u	45	21	-	-
Cocos Island	v	32	60	34	-

TABLE XVIIIB

PHASE DIFFERENCE BETWEEN 850 MB AND OTHER LEVELS IN HUNDREDTHS OF A CYCLE FOR 10-17 DAY FLUCTUATIONS IN THE WINTER SEASON. VALUES IN PARENTHESES ARE ASSOCIATED WITH COHERENCE SQUARE VALUES BETWEEN 90 AND 95% LEVELS OF CONFIDENCE.

Station	Parameter	700mb	500mb	300mb	200mb
Gan	u	-02	(-07)	-10	-
Gan	v	01	-	34	50
Minicoy	u	-	-	-	-45
Minicoy	v	05	-11	-	-
Singapore	u	04	00	-	-
Singapore	v	-10	-14	-44	-35
Dar-es-Salaam	u	00	-	-	(23)
Dar-es-Salaam	v	-10	36	09	-25
Cocos Island	u	00	-04	-	-
Cocos Island	v	-11	08	01	-

TABLE XIXA

COHERENCE SQUARE BETWEEN 850 MB AND OTHER LEVELS IN HUNDREDS FOR 10-17 DAY FLUCTUATIONS IN THE SUMMER SEASON.

Station	Parameter	700mb	500mb	300mb	200mb
Gan	u	19	19	30	21
Gan	v	18	-	-	35
Singapore	u	59	43	-	19
Singapore	v	59	29	26	19
Dar-es-Salaam	u	15	-	43	32
Dar-es-Salaam	v	-	-	52	20
Cocos Island	u	71	20	-	-
Cocos Island	v	62	42	50	44

TABLE XIXB

PHASE DIFFERENCE BETWEEN 850 MB AND OTHER LEVELS IN HUNDREDTHS OF A CYCLE FOR 10-17 DAY FLUCTUATIONS IN THE SUMMER SEASON.

Station	Parameter	700mb	500mb	300mb	200mb
Gan	u	-19	-28	-21	-11
Gan	v	(05)	-	-	17
Singapore	u	03	11	-	46
Singapore	v	-10	-07	-15	06
Dar-es-Salaam	u	(-06)	-	41	50
Dar-es-Salaam	v	-	-	-34	19
Cocos Island	u	-04	-16	-	-
Cocos Island	v	-07	-06	-05	-06

TABLE XXA

COHERENCE-SQUARE IN HUNDREDTHS BETWEEN FLUCTUATIONS IN u AND v AT 850, 700, AND 300 MB IN THE 10-17 DAY PERIOD RANGE. VALUES > .15 AND .19 ARE SIGNIFICANT TO THE 90% AND 95% LEVELS, RESPECTIVELY.

Station	Season	850mb	700mb	300mb
Gan	Winter	-	-	-
Gan	Summer	28	15	-
Minicoy	Winter	15	21	-
Singapore	Winter	18	20	-
Singapore	Summer	16	26	-
Cocos Island	Winter	17	-	22
Cocos Island	Summer	49	-	49

TABLE XXB

PHASE DIFFERENCE IN HUNDREDTHS OF A CYCLE BETWEEN FLUCTUATIONS IN u AND v AT 850, 700 AND 300 MB IN THE 10-17 DAY PERIOD RANGE. POSITIVE VALUES INDICATE v LEADS u.

Station	Season	850mb	700mb	300mb
Gan	Winter	-	-	-
Gan	Summer	-20	(-11)	-
Minicoy	Winter	(-37)	31	-
Singapore	Winter	(-10)	12	-
Singapore	Summer	(-08)	13	-
Cocos Island	Winter	(-43)	-	-35
Cocos Island	Summer	44	-	-19

TABLE XXI

COHERENCE SQUARE IN HUNDREDTHS AND PHASE DIFFERENCE IN HUNDREDTHS OF A CYCLE [IN BRACKETS] BETWEEN PAIRS OF STATIONS FOR 10-17 DAY FLUCTUATIONS. THE FIRST STATION LISTED IS THE BASE SERIES AND A POSITIVE VALUE OF PHASE INDICATES THAT THIS SERIES LEADS THE OTHER.

Stations	850mb u	850mb v	700mb u	700mb v	300mb u	300mb v
a. Winter						
Gan - Minicoy	-	15 [-36]	18 [47]	-	16 [-11]	15 [-48]
Gan - Singapore	27 [-09]	-	-	-	30 [-19]	-
Singapore- Minicoy	-	-	-	17 [39]	16 [-22]	-
Singapore- Cocos Island	20 [10]	-	-	-	-	19 [-24]
b. Summer						
Gan - Singapore	26 [-27]	18 [-19]	-	-	-	24 [-41]
Singapore- Cocos Island	20 [03]	28 [34]	29 [00]	-	-	43 [-39]

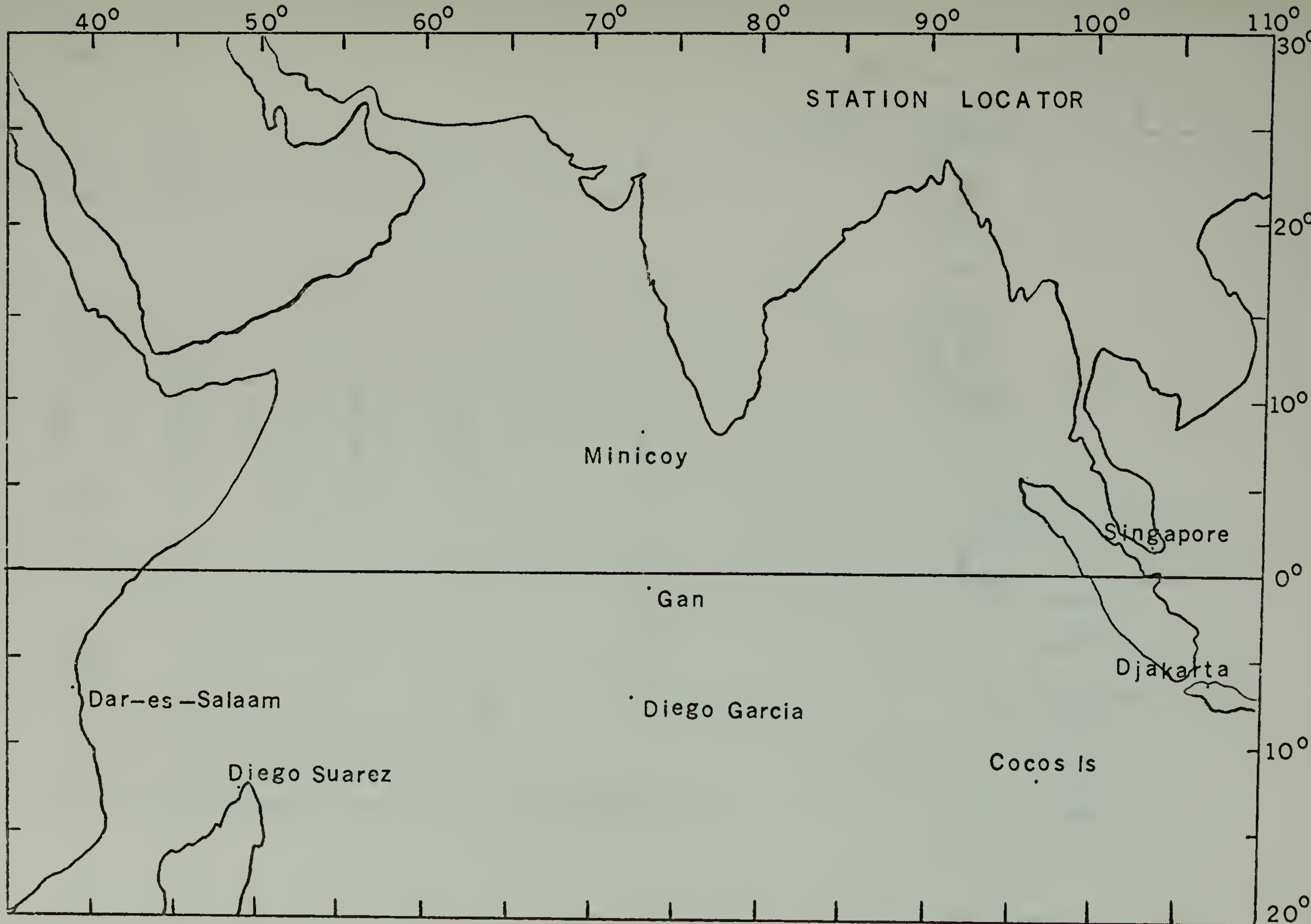

Figure 1. Geographical Locations of Stations.

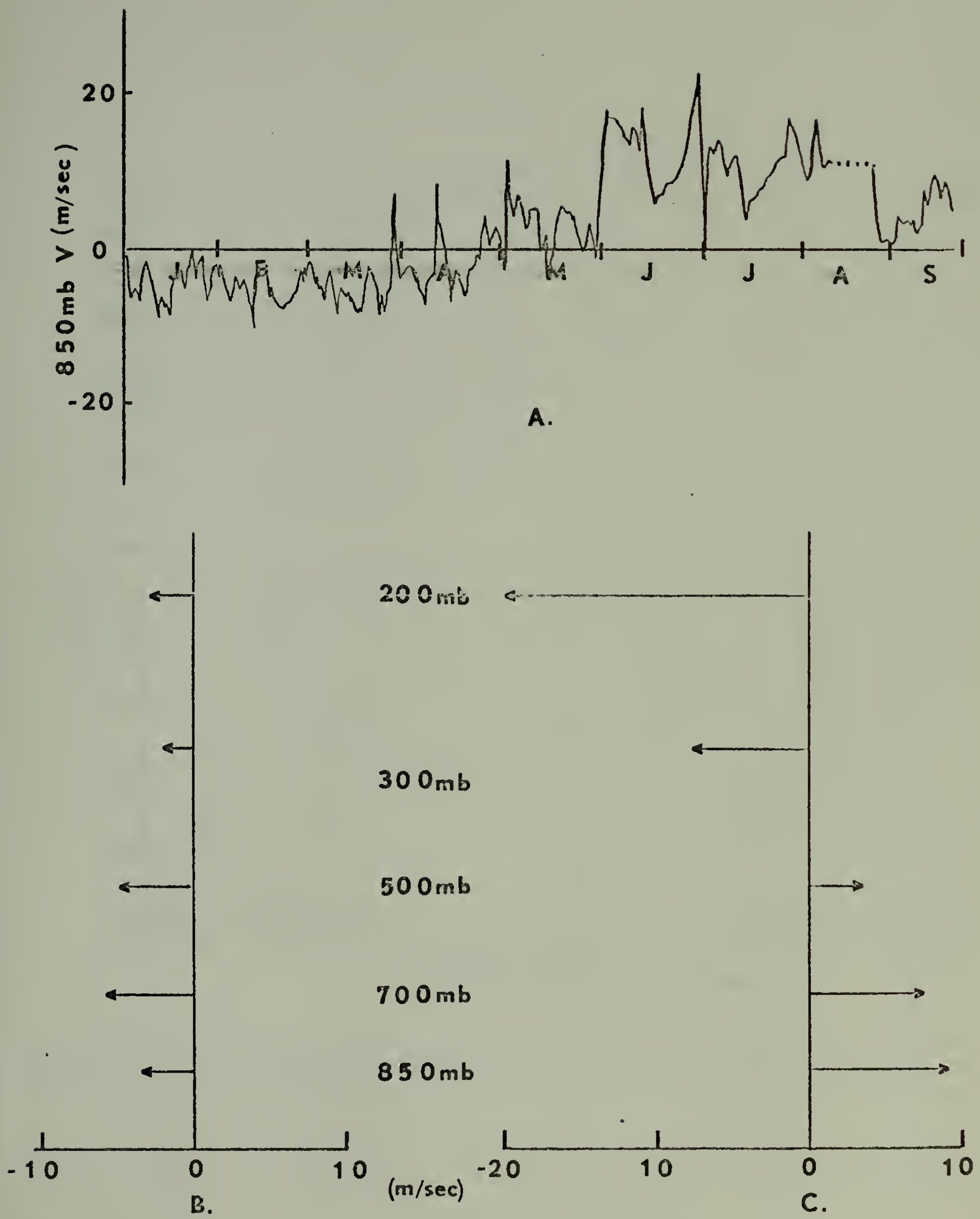

Figure 2A. The monsoon shift at Minicoy shown in the time series of 850 mb meridional wind. B and C. The vertical profile of mean zonal wind at Minicoy for the winter and summer seasons.

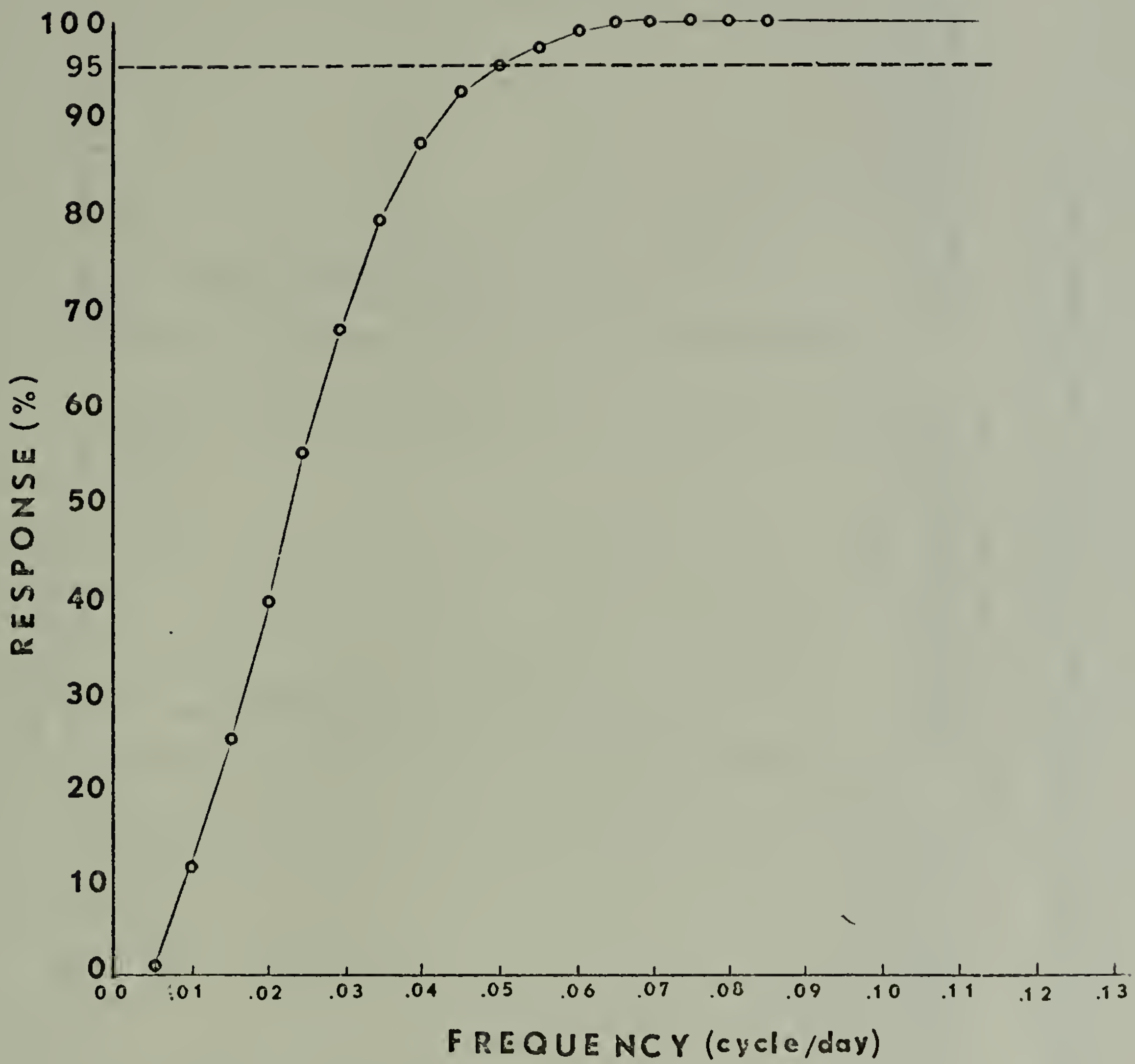

Figure 3. Frequency response of high pass Gaussian filter with σ = 8.

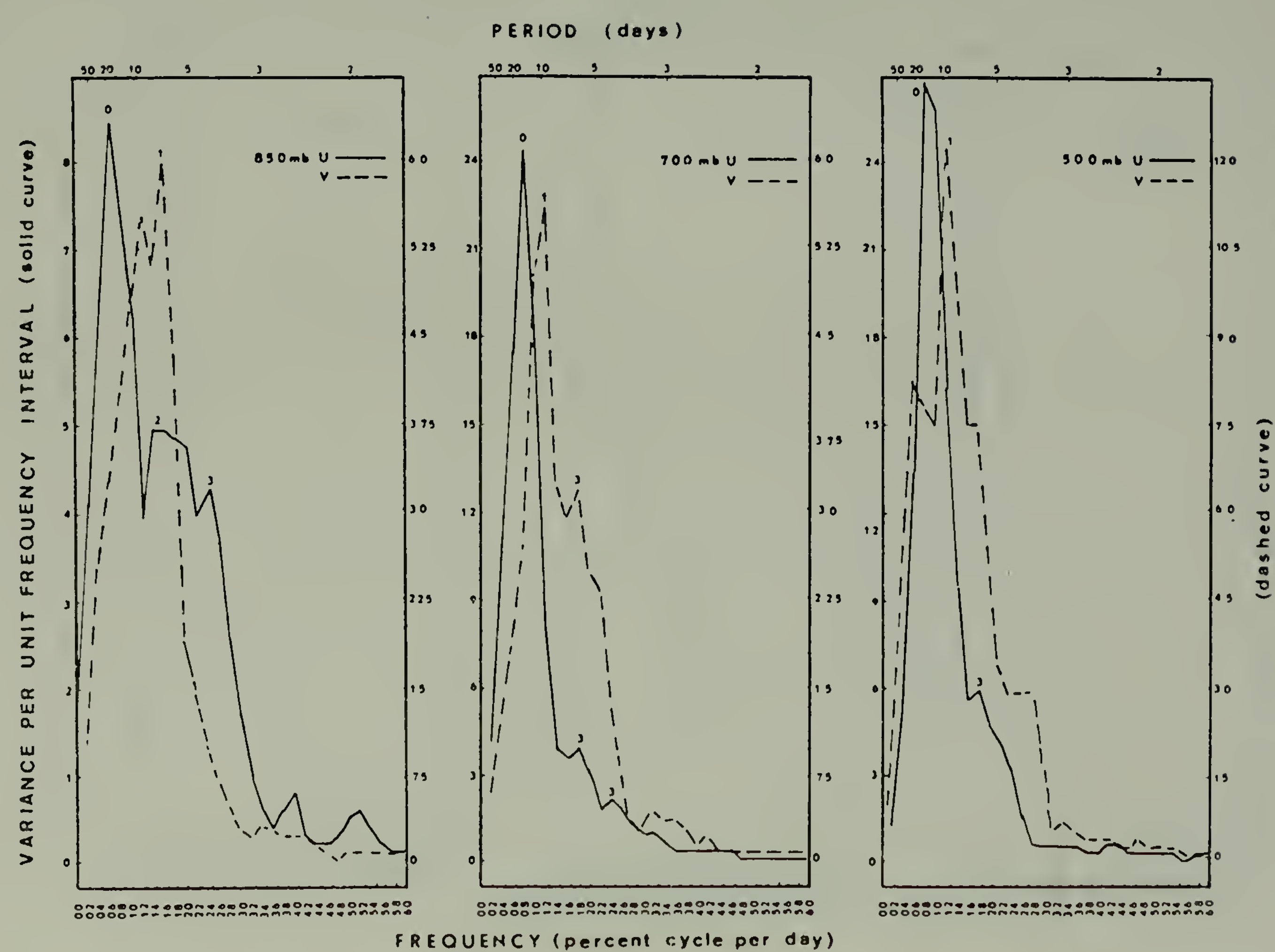

Figure 4A. Spectral estimates of time series at Gan in the winter season.

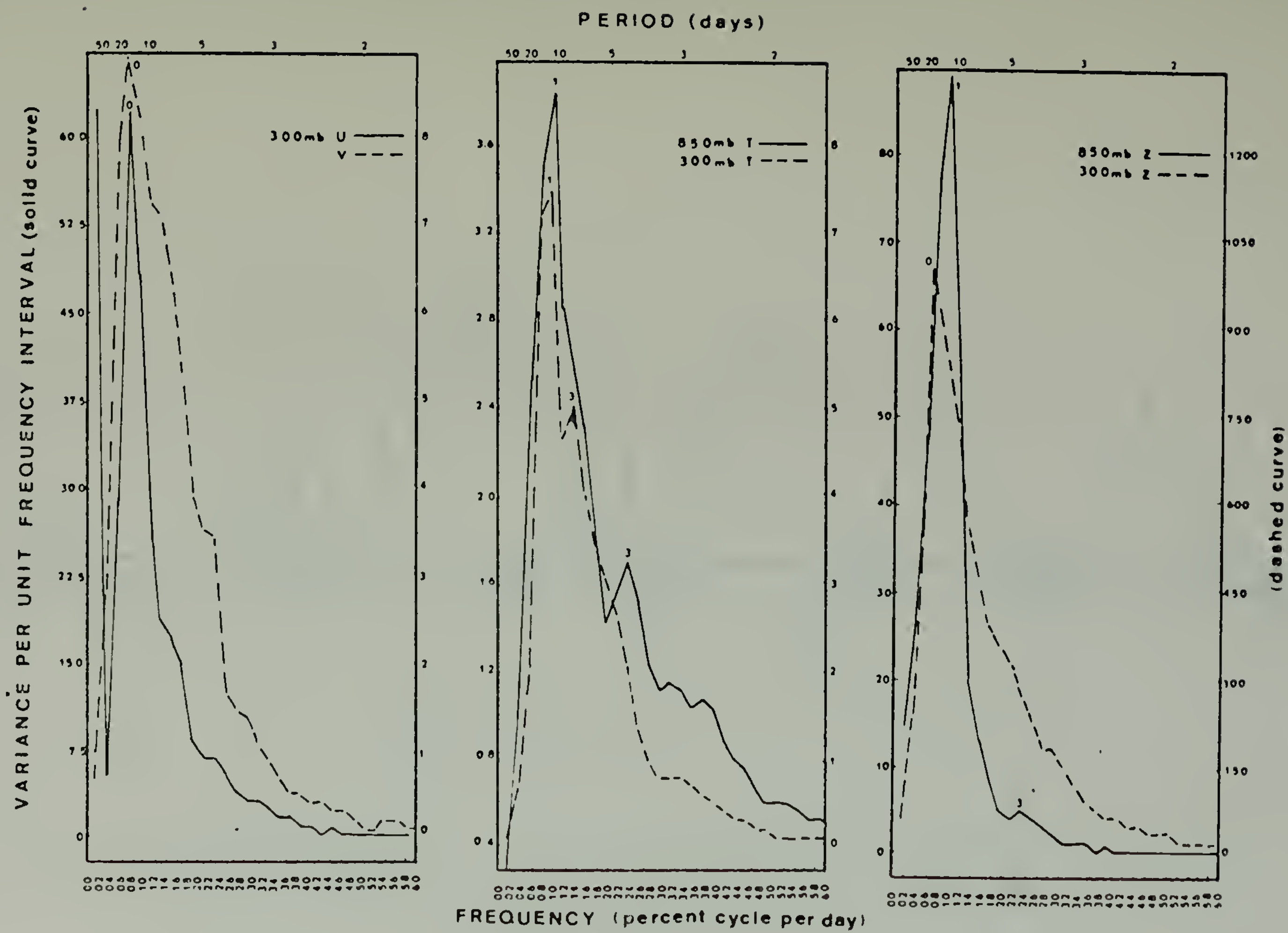

Figure 4B. Spectral estimates of time series at Gan in the winter season.

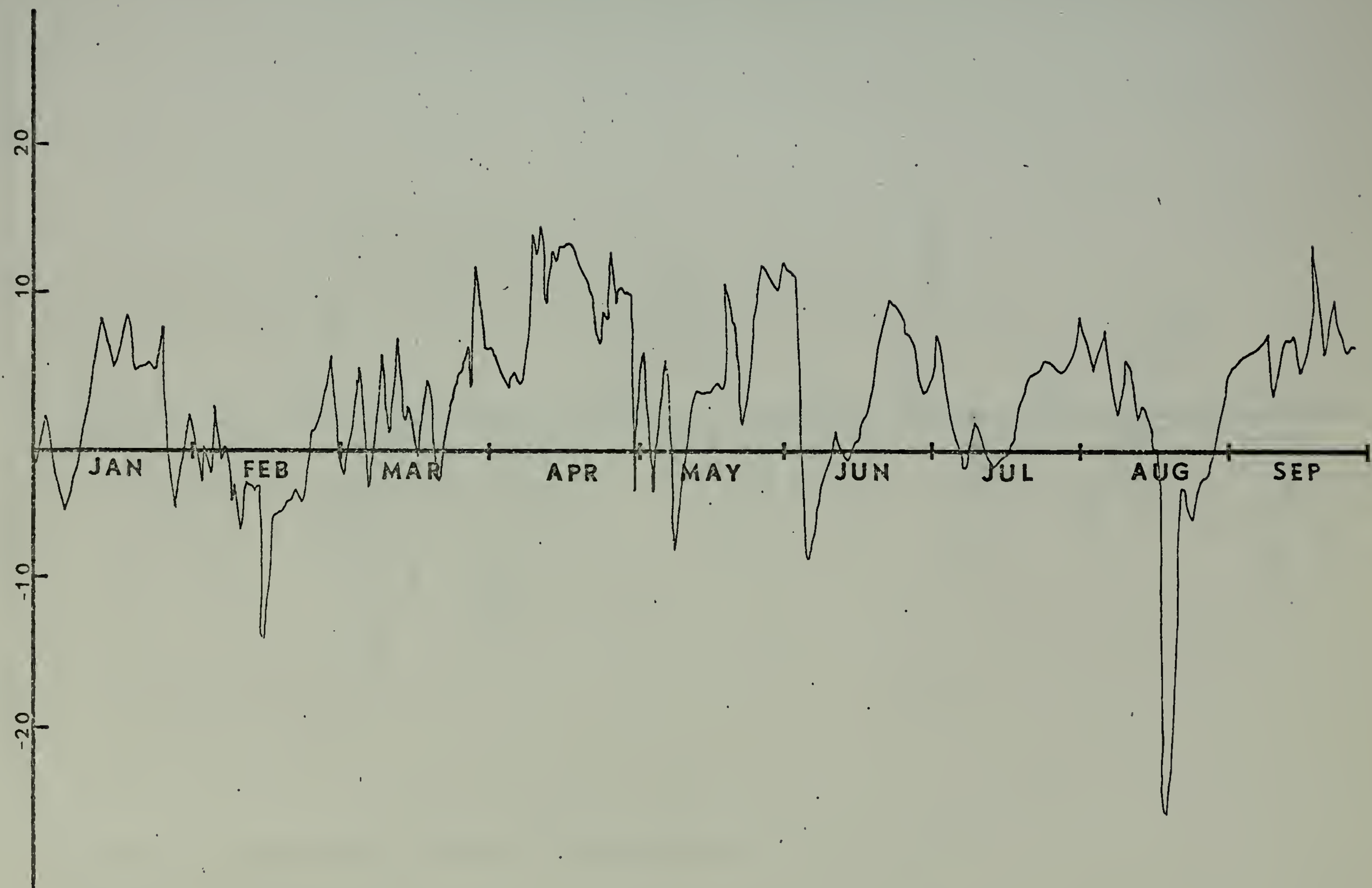

Figure 5. Time series of 850 mb zonal wind (m/sec) at Gan.

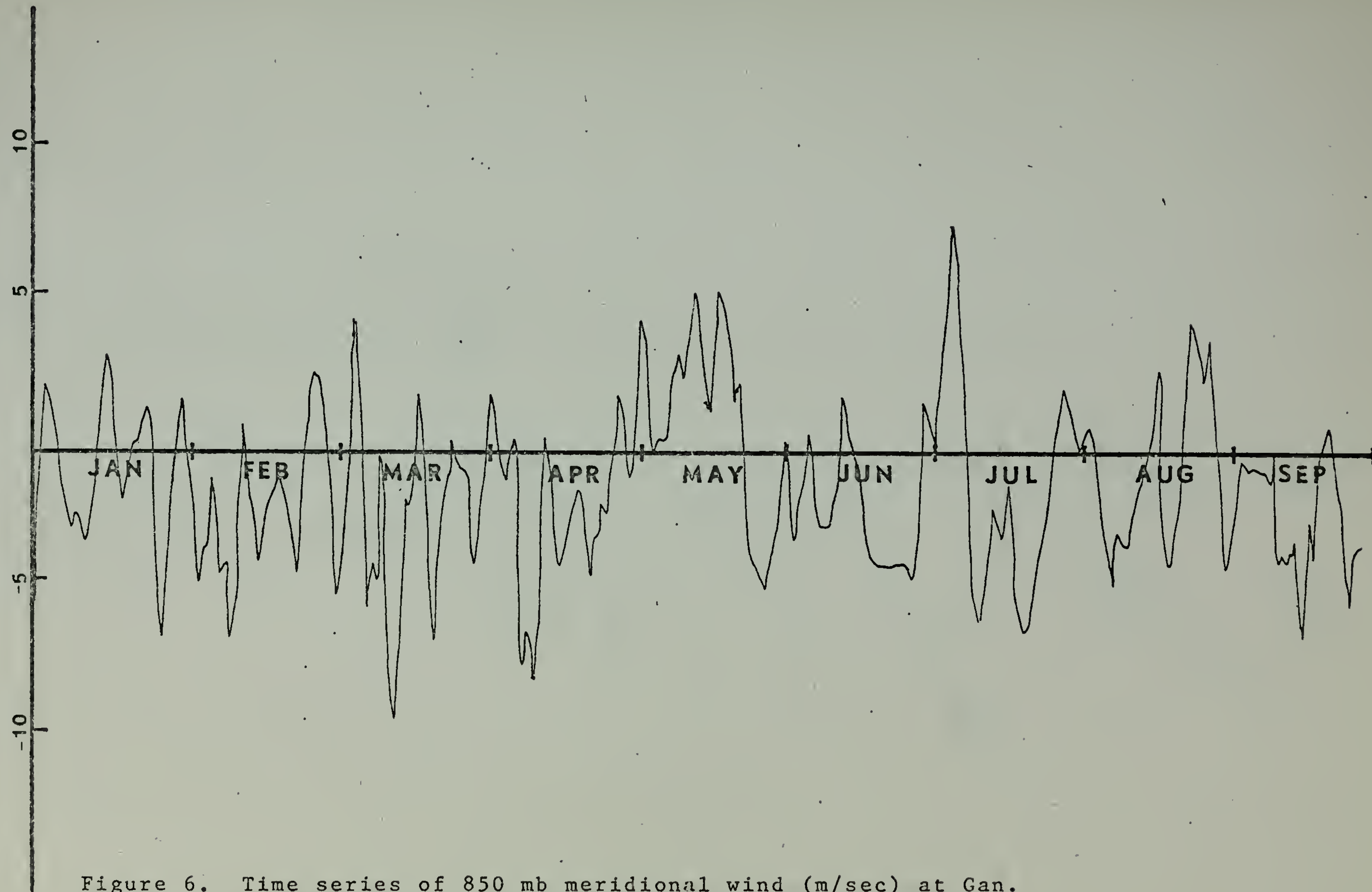

Figure 6. Time series of 850 mb meridional wind (m/sec) at Gan.

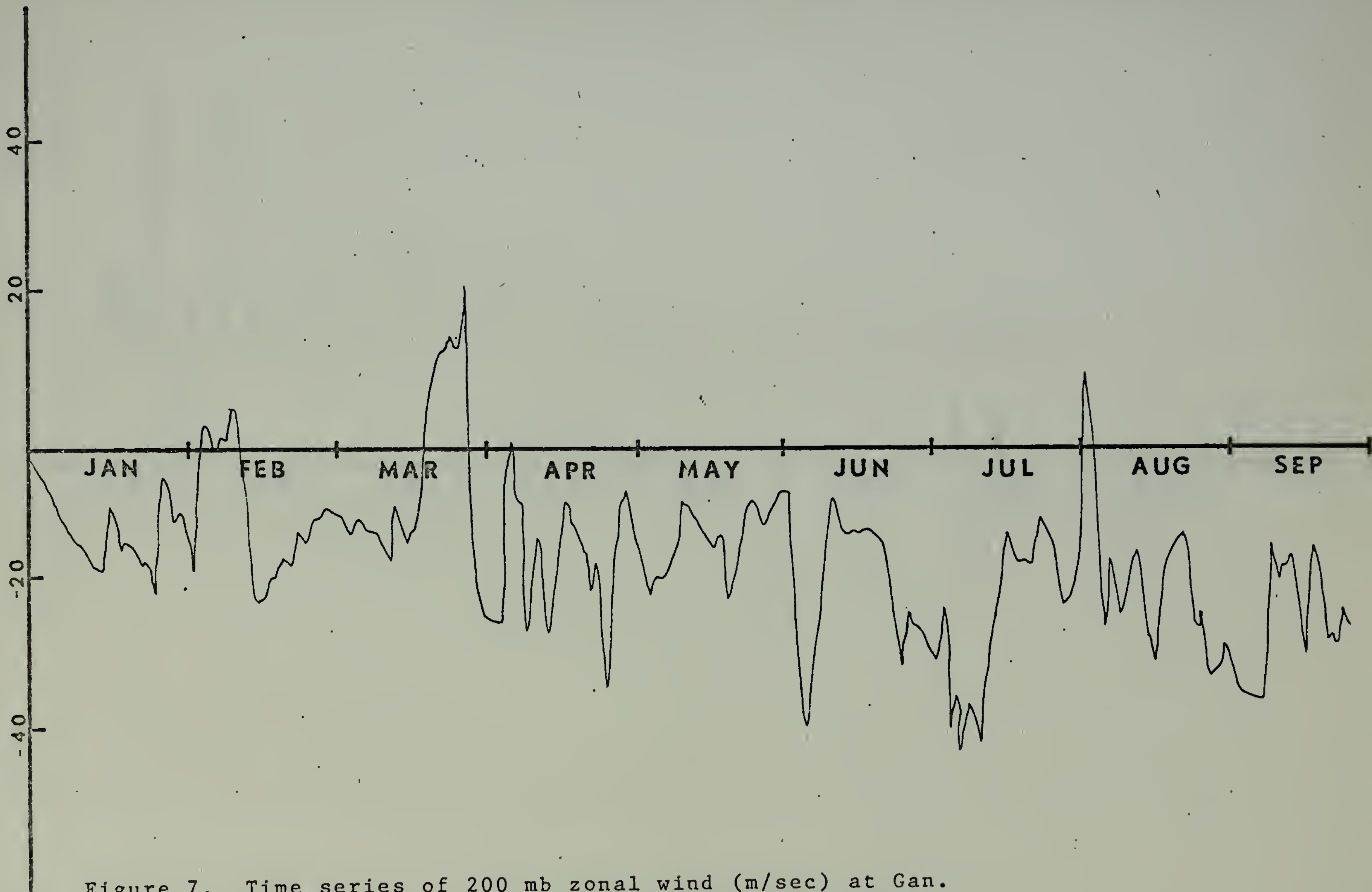

Figure 7. Time series of 200 mb zonal wind (m/sec) at Gan.

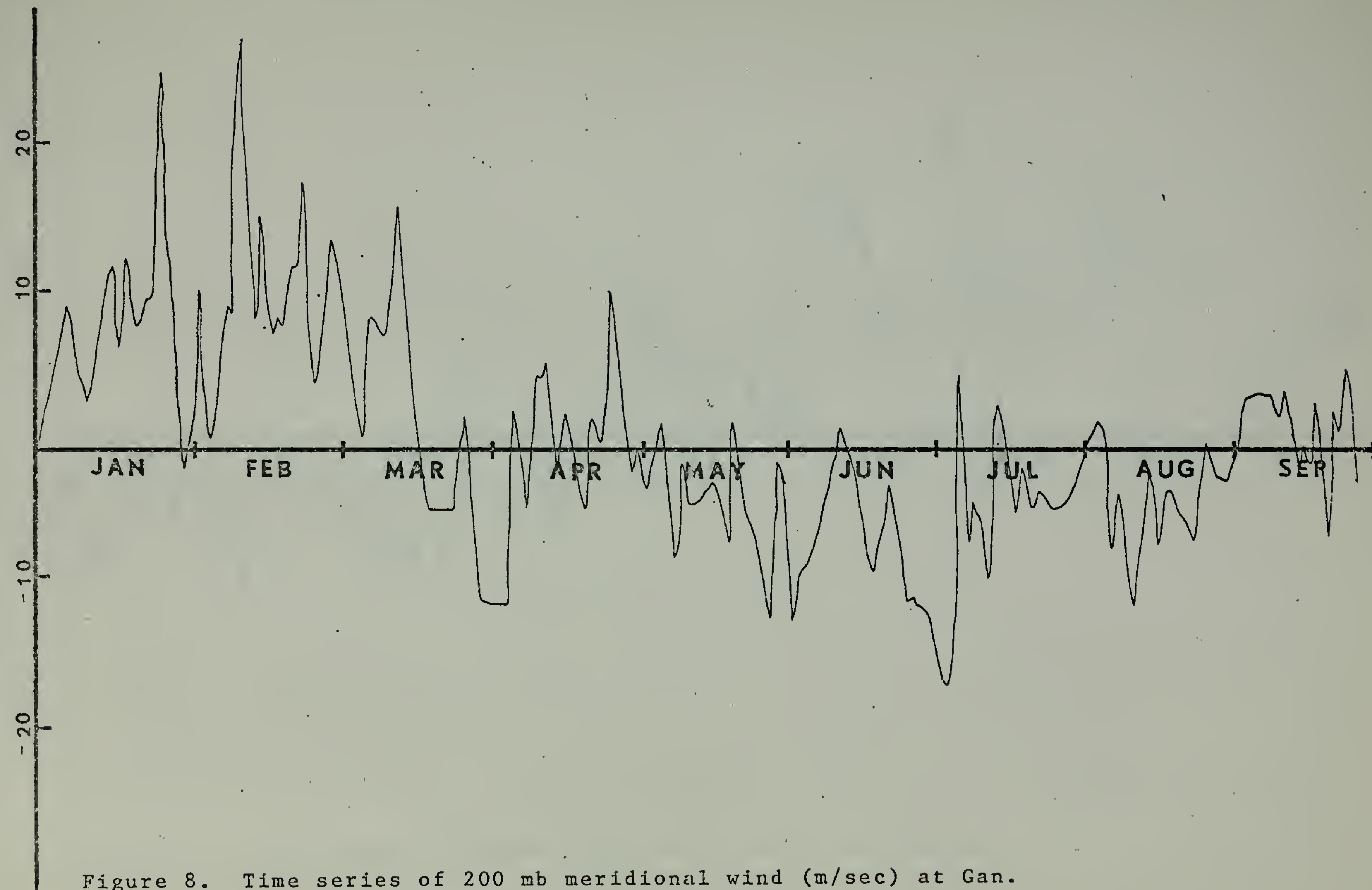

Figure 8. Time series of 200 mb meridional wind (m/sec) at Gan.

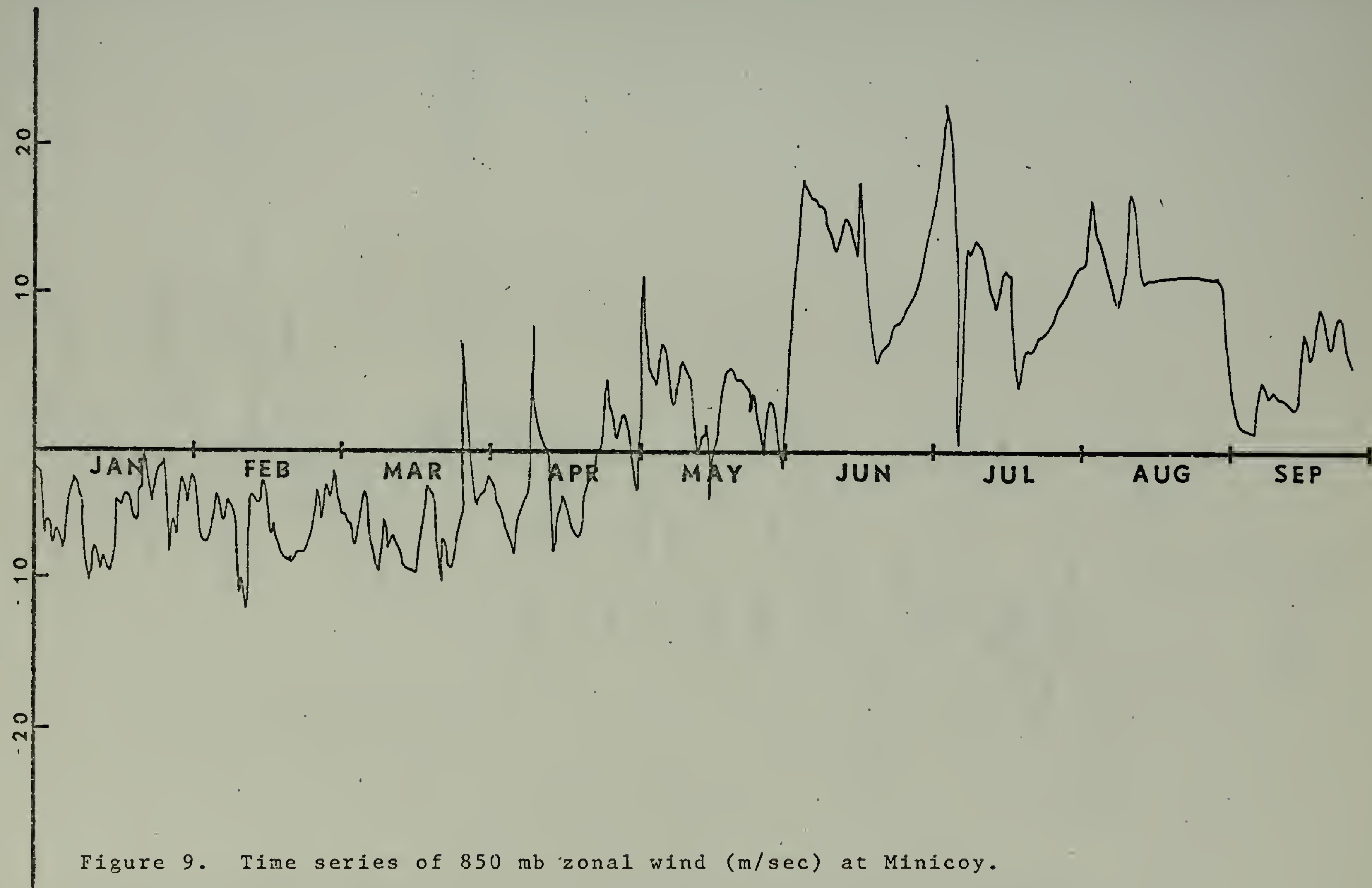

Figure 9. Time series of 850 mb zonal wind (m/sec) at Minicoy.

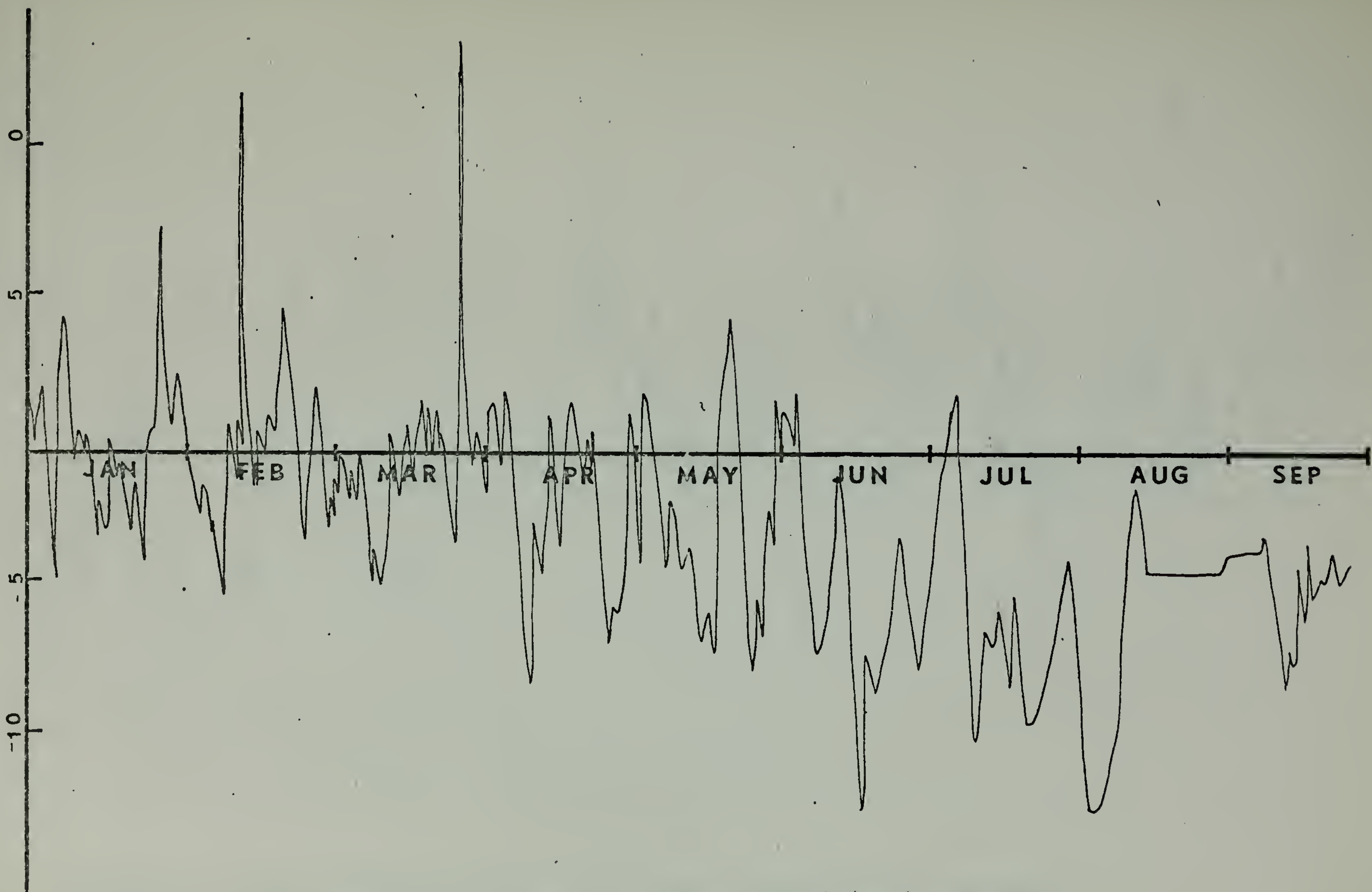

Figure 10. Time series of 850 mb meridional wind (m/sec) at Minicoy.

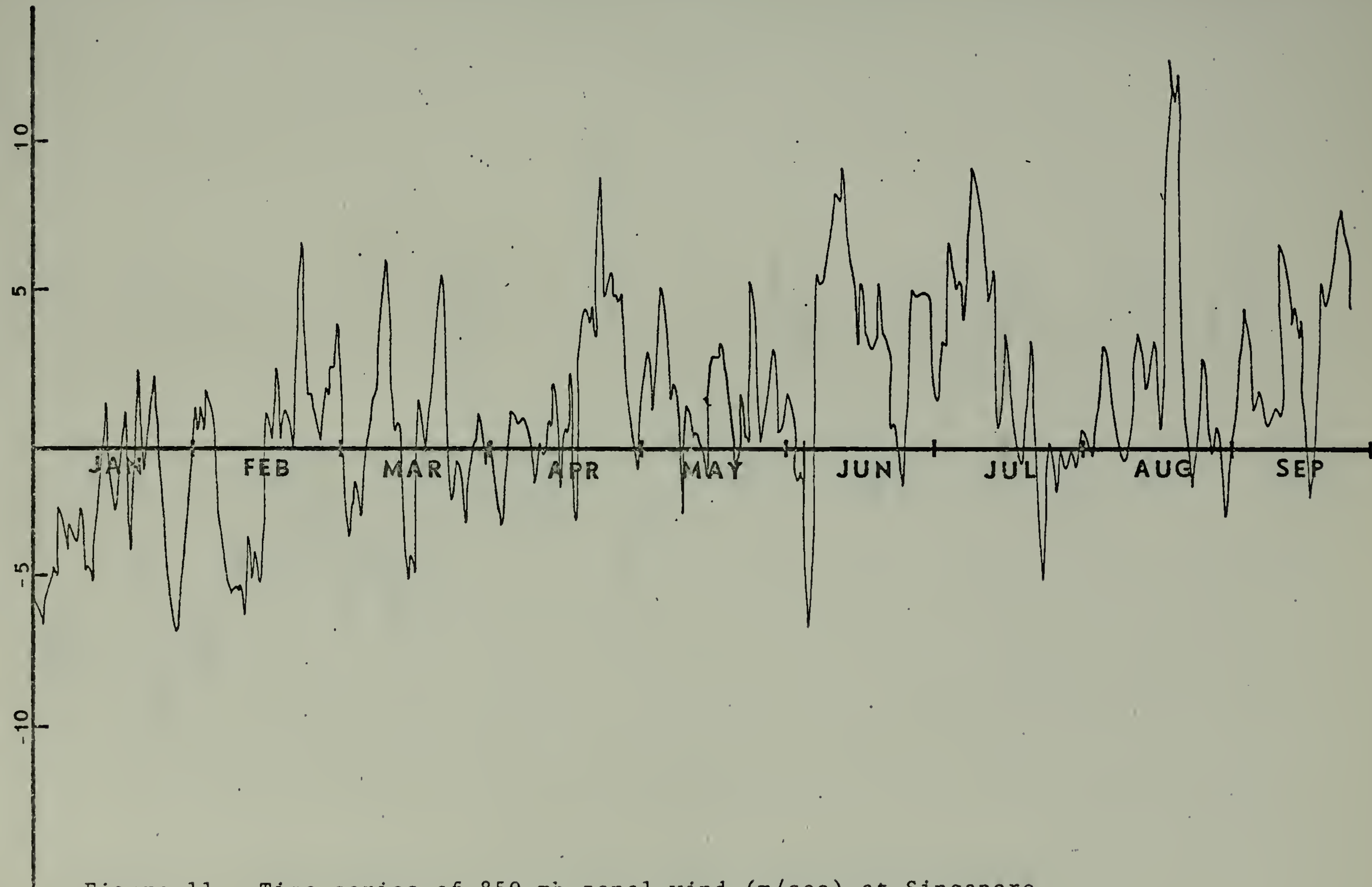

Figure 11. Time series of 850 mb zonal wind (m/sec) at Singapore.

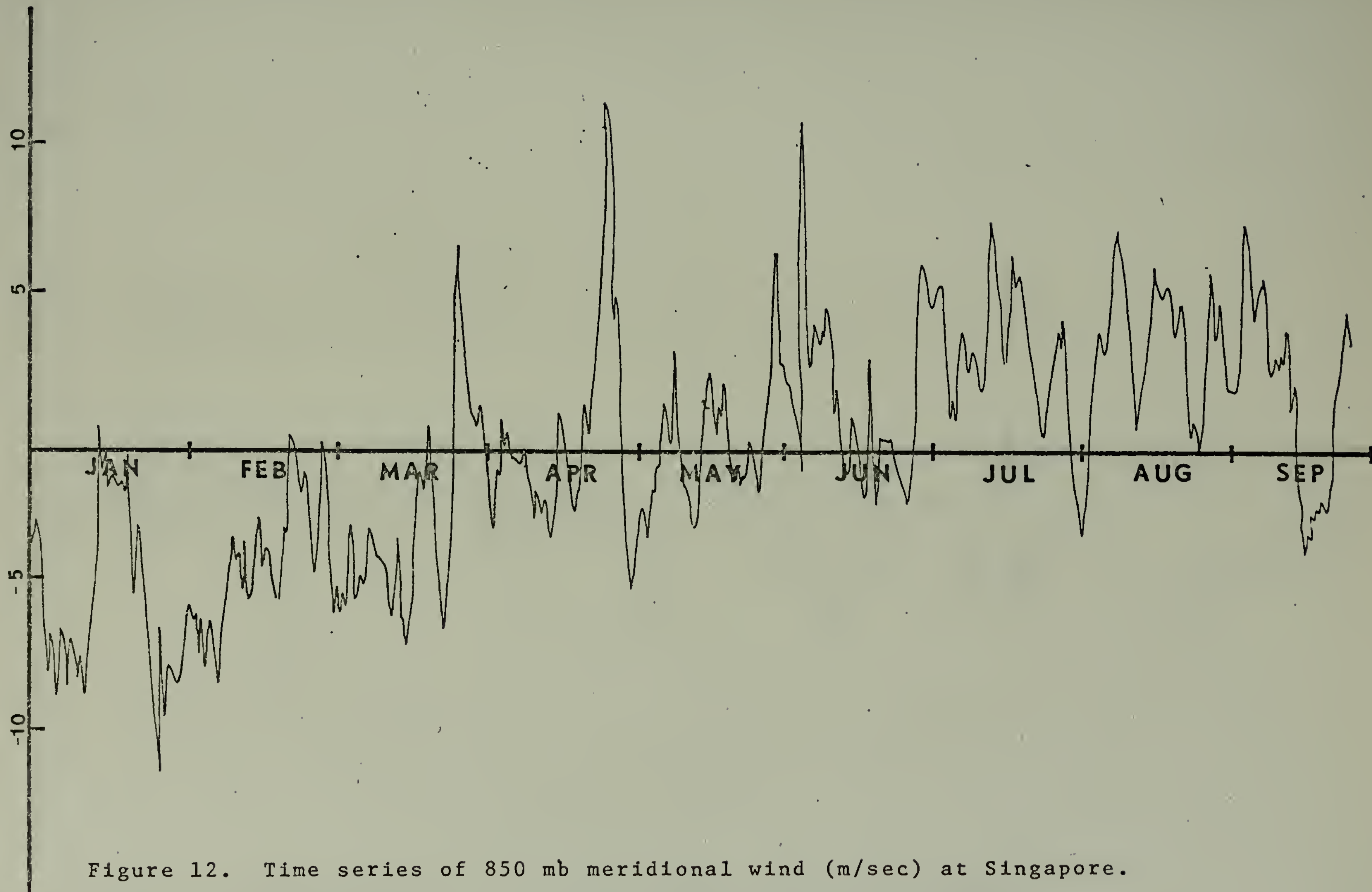

Figure 12. Time series of 850 mb meridional wind (m/sec) at Singapore.

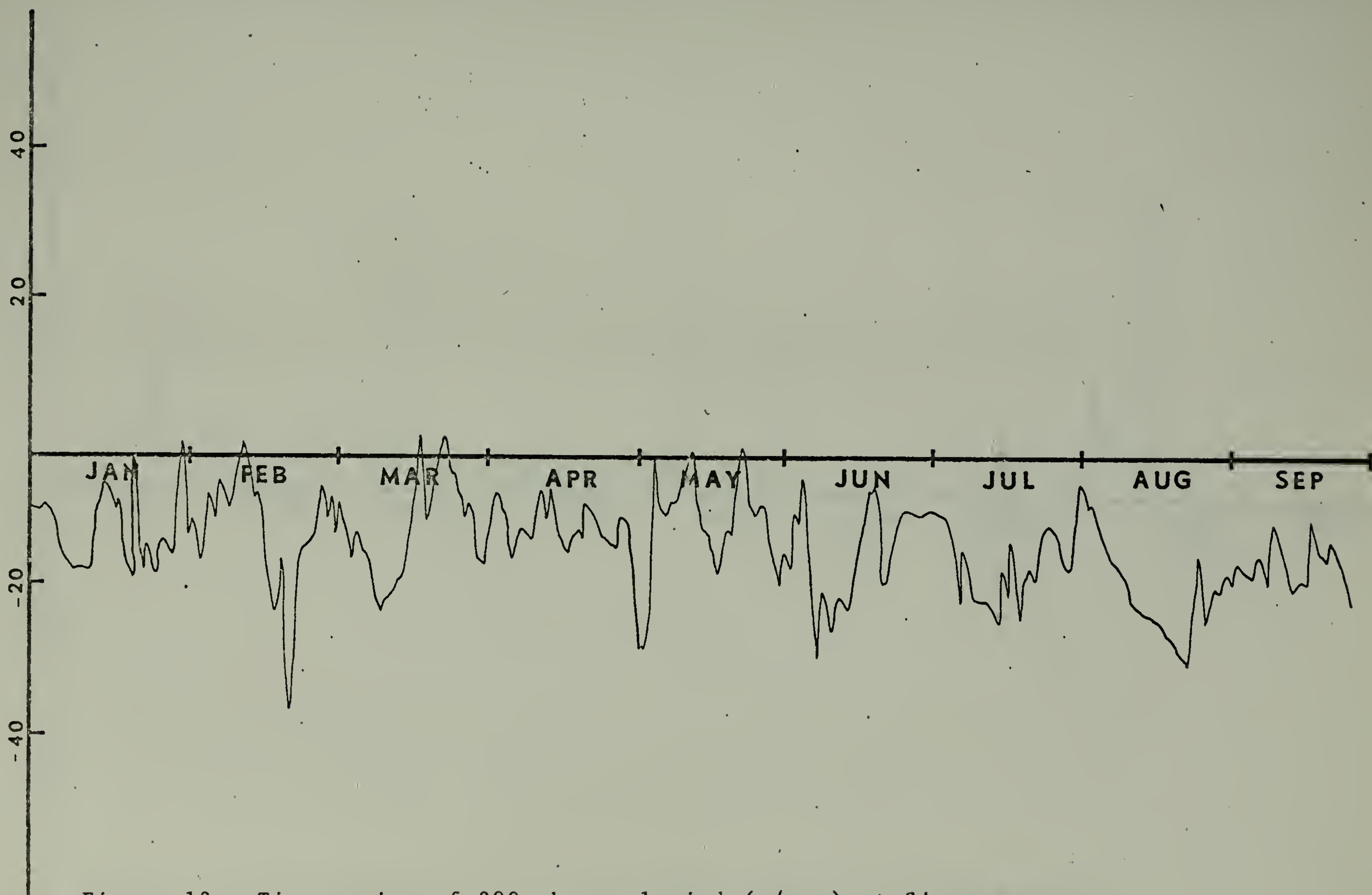

Figure 13. Time series of 200 mb zonal wind (m/sec) at Singapore.

Figure 14. Time series of 200 mb meridional wind (m/sec) at Singapore.

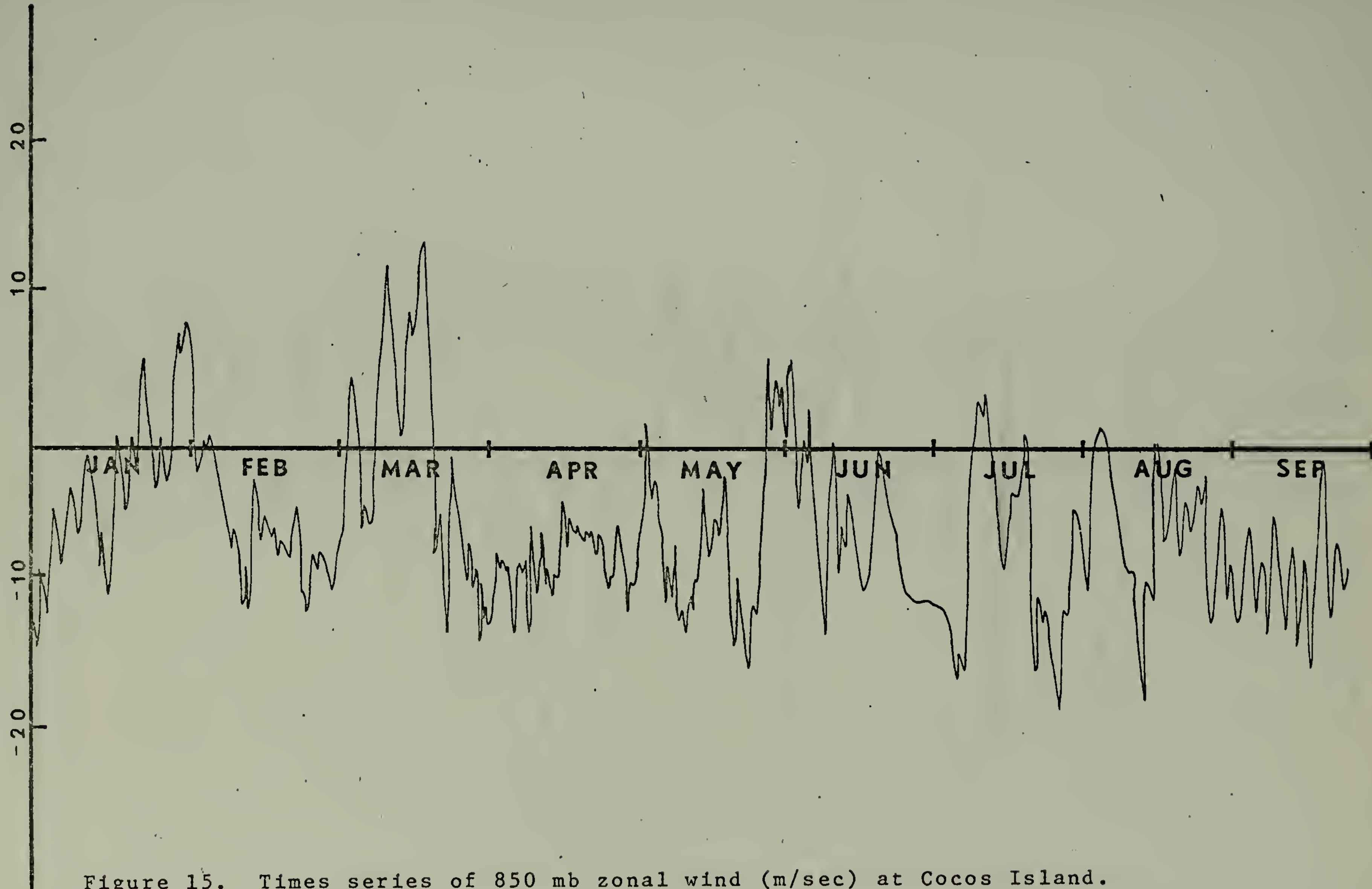

Figure 15. Times series of 850 mb zonal wind (m/sec) at Cocos Island.

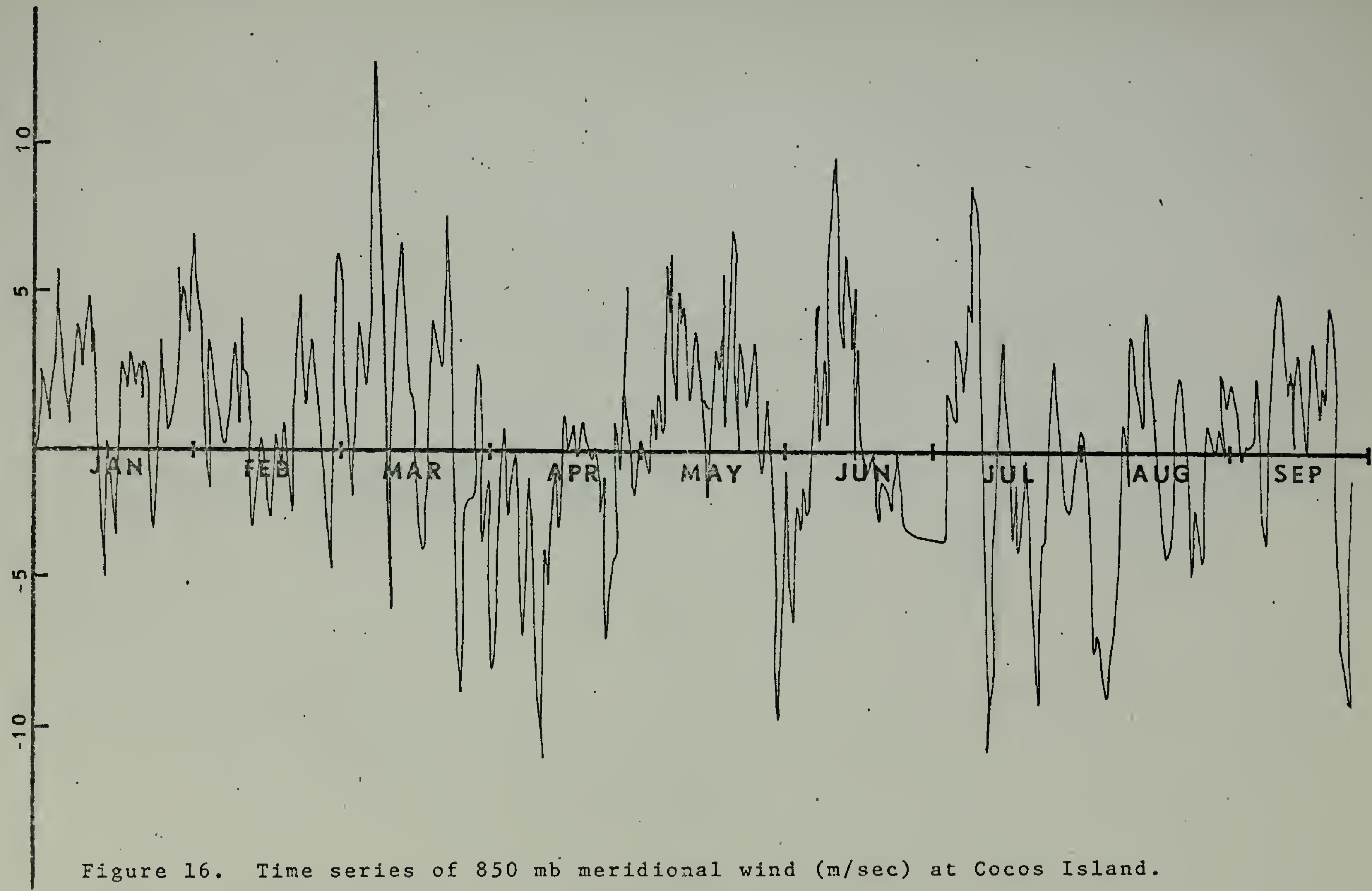

Figure 16. Time series of 850 mb meridional wind (m/sec) at Cocos Island.

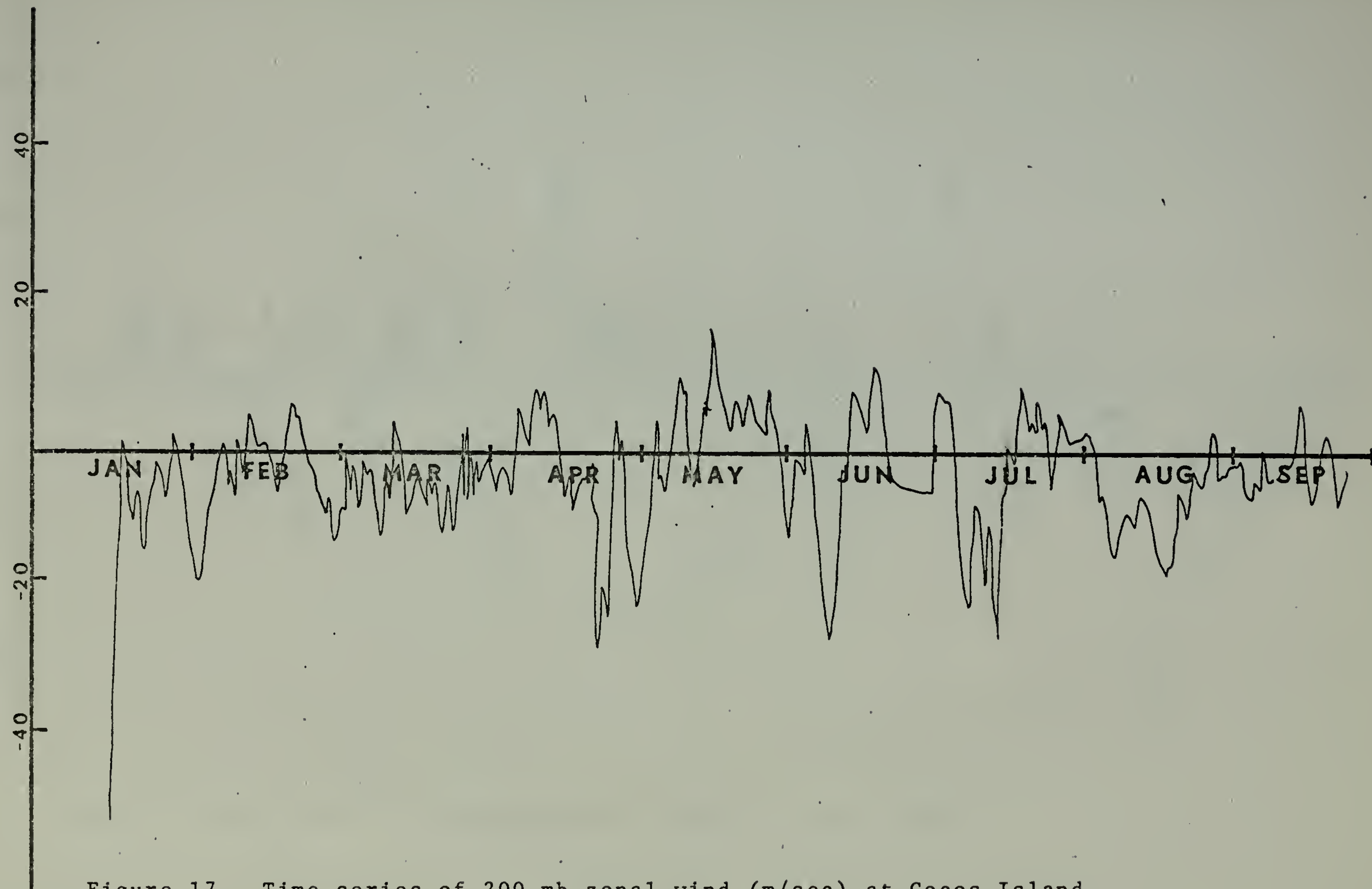

Figure 17. Time series of 200 mb zonal wind (m/sec) at Cocos Island.

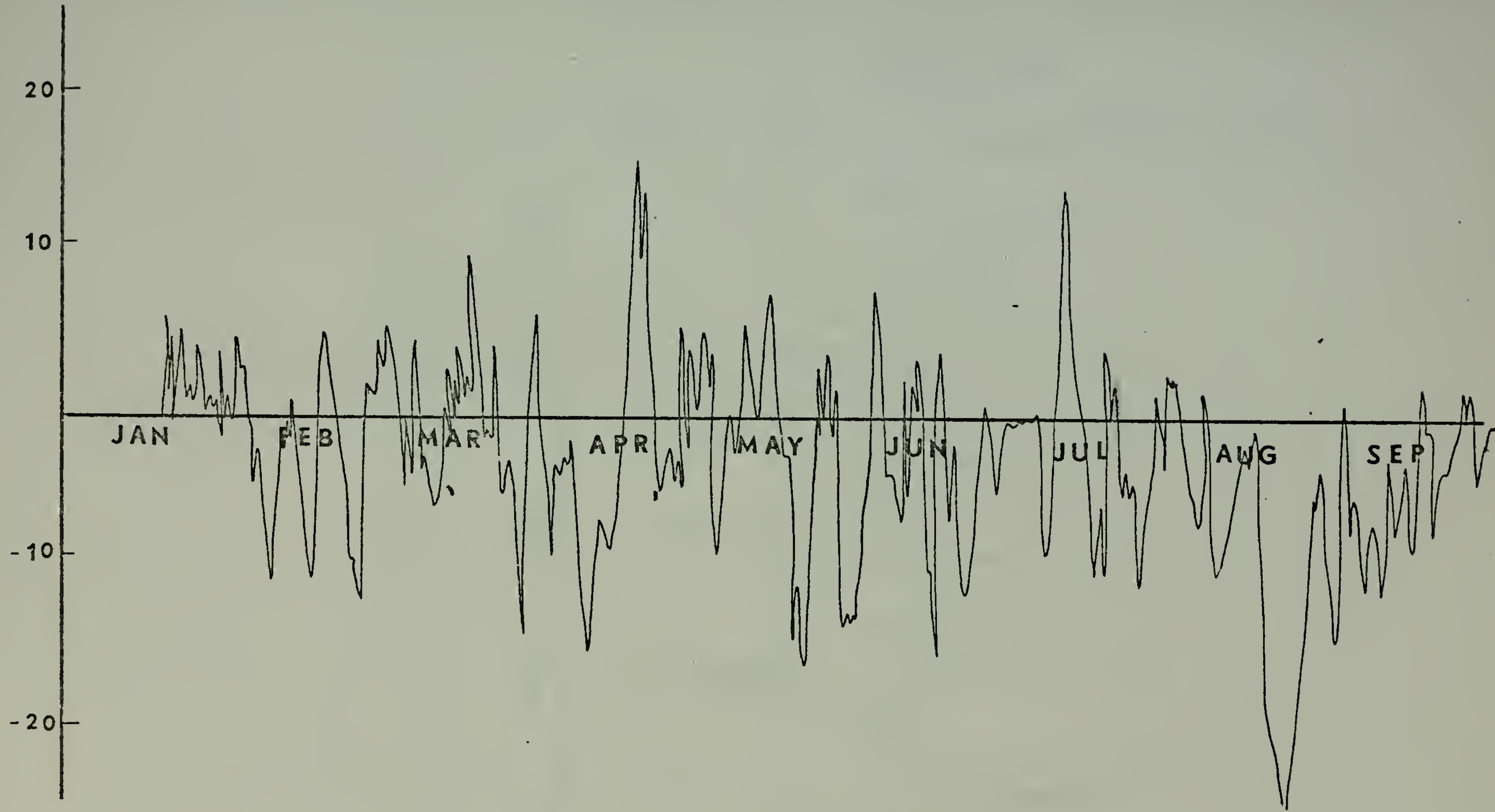

Figure 18. Time series of the meridional wind component at Cocos Island.

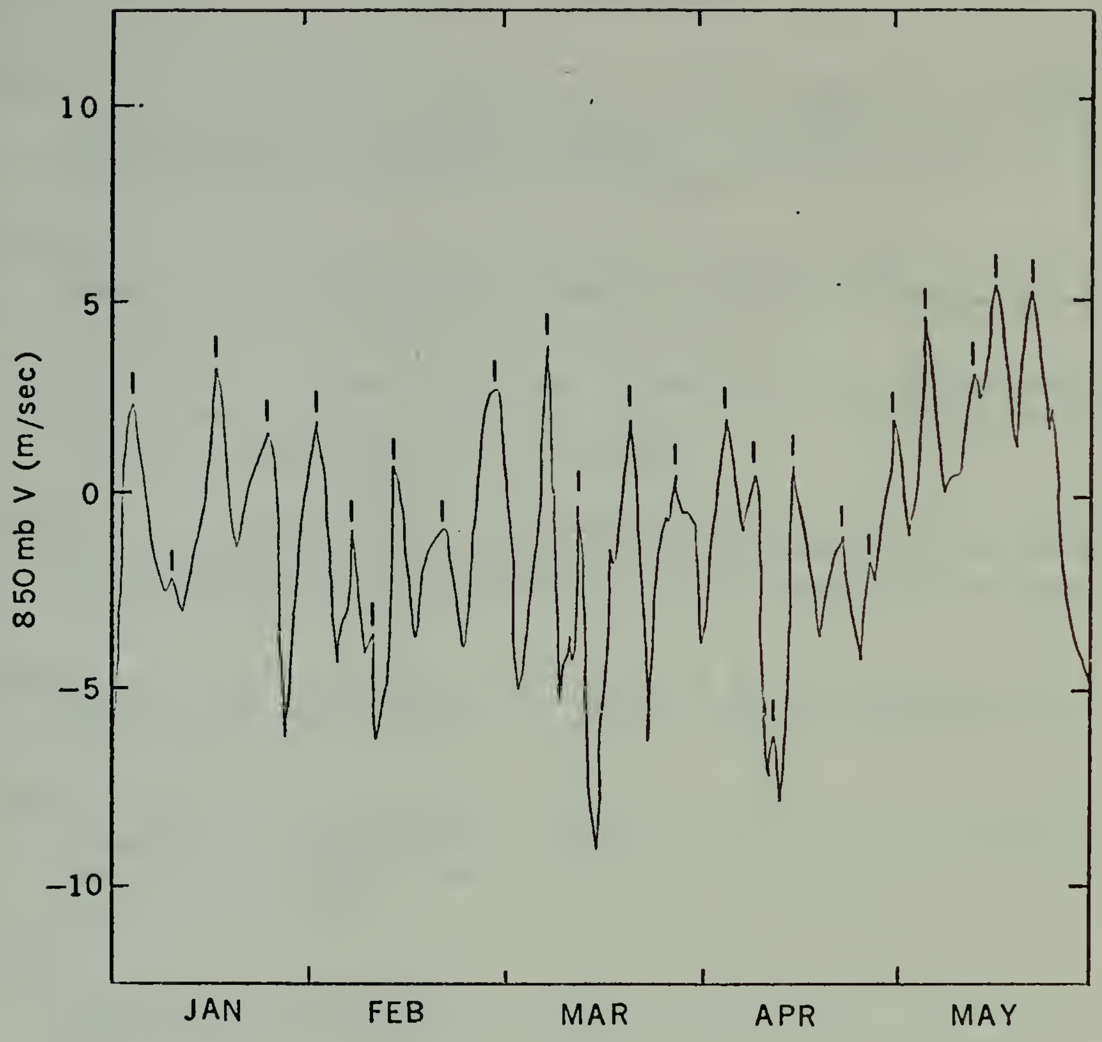

Figure 19. Five month time series of 850-mb v at Gan showing 6-7 day periodicity.

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